USING THE LAKE TROUT AS AN INDICATOR OF ECOSYSTEM HEALTH—

APPLICATION OF THE DICHOTOMOUS KEY

Great Lakes Fishery Commission

TECHNICAL REPORT No. 49

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USING THE LAKE TROUT AS AN INDICATOR OF ECOSYSTEM HEALTH-

APPLICATION OF THE DICHOTOMOUS KEY

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In Memoriam

We dedicate the Lake Trout Dichotomous Key to the memory of Nigel V. Martin, who devoted his life to the improved understanding of the lake trout. His contributions to lake trout lore have won him the respect of fishery scientists throughout the world. His concern for the future of this sensitive species is reflected in the wealth of scientific information he has provided to fishery managers responsible for the conservation and wise use of the lake trout resource.

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EXECUTIVE SUMMARY

The lake trout, *Salvelinus namaycush* (Walbaum), has been proposed for use as an indicator of ecosystem quality for the Great Lakes basin (Ryder and Edwards eds. 1985). In order to apply the concept for the effective management of aquatic systems, a Dichotomous Key has been devised, which is designed to pose critical questions pertaining to the lake trout, its aquatic community associates, and its environment. Specifically, the questions refer to the niche characteristics and habitat requirements of healthy lake trout stocks. Responses to these questions provide the requisite information from which the current state of ecosystem health is assessed. It was assumed that the lake trout, with its rigorous environmental requirements, would serve as an apposite surrogate for a healthy oligotrophic system.

The Dichotomous Key has been designed as a menu-driven computer program which may be easily implemented by the ecosystem manager and layman alike. It is an interactive program in that the users may revise their inputs as new information becomes available. The program also provides the rationale behind each of the questions in the Key as well as bibliographic documentation for the rationale.

Use of the Dichotomous Key program should provide a greater perception of which particular stresses are adversely affecting ecosystem “health”. In addition, the program tends to draw to the user’s attention, low profile stresses which may be critical to the persistence of a healthy ecosystem.

The Lake Trout Dichotomous Key program for Lake Superior is available free of charge from the senior author, with versions for Commodore, Apple II, and IBM microcomputers.

INTRODUCTION

The most recent Great Lakes Water Quality Agreement (1978) between Canada and the United States was an acknowledgment of the continuing degradation of the Great Lakes Basin ecosystem. Its purpose was the restoration and maintenance of "the chemical, physical, and biological integrity of the waters of the Great Lakes Basin Ecosystem". A Work Group reporting to the Science Advisory Board of the International Joint Commission (IJC), concluded that certain biological attributes of the Great Lakes might serve as utilitarian indicators of the "health" of the ecosystem. This concept was recently implemented by a recent cooperative initiative of the IJC and the Great Lakes Fishery Commission (GLFC). Specifically, a proposal was made whereby the lake trout, *Salvelinus namaycush* (Walbaum), may be used as an indicator of ecosystem health (Ryder and Edwards eds. 1985).

This conceptual approach was developed by the Work Group. It first established requisite criteria for an appropriate indicator organism, and then set out to find taxa native to the Great Lakes that best fit the proposed criteria (Ryder and Edwards eds. 1985). A subset of these criteria for an ideal indicator organism required that: baseline historical records on abundance of the indicator organism be available; it be an integrator of the cold-water community in which it plays a key ecological role, and therefore, a terminal predator; it have wide distribution within oligotrophic environments: it have an extensively quantified and well-documented niche envelope; its habitat requirements be comprehensively understood and documented; it exhibit at least a moderate degree of phenotypic diversity; it be susceptible to, or reflect in various ways, most interventions of cultural origin; it have a high human value and a ready recognition by humans. Other criteria were considered to be relatively less important, but sufficiently useful to be recorded.

Of the many prospective candidate organisms considered, the lake trout came closest to fitting this requisite set of criteria. The implementation of such an "umbrella" organism as an ecosystem indicator was serendipitous to a certain degree. For example, a particular ecosystem requirement designed to ensure abundant, reproducing, diverse stocks of lake trout, would almost certainly protect most other constituents of a cold-water community, many of which have environmental needs much less rigorous than those of lake trout. Accordingly, the "health" of lake trout stocks in terms of abundance, growth, natural reproduction, phenotypic diversity and other desirable attributes would almost certainly ensure a moderately "stable" and "balanced" cold-water community, in addition to an appropriate supportive milieu. This concept was expanded subsequently, so that an ecosystem objective for management purposes might be based on observations of the relative well-being of the lake trout (Ryder and Edwards eds. 1985).

With the conceptual stage set for using the lake trout both as a surrogate for the cold-water community and as a benchmark for the oligotrophic environment, the Work Group studied the various possibilities for a pragmatic application that might be used by ecosystem managers for identifying cultural degradation of an ecosystem. Accordingly, the Lake Trout Dichotomous Key was conceived as a utilitarian method holding promise for the application of sometimes inordinately complex or profound concepts, to a practical problem of multiple stress identification.

The Dichotomous Key was designed as a computer program which, in its current version, assesses the relative well-being of lake trout stocks in Lake Superior. The user is presented with a series of questions dealing with specific concerns within the broad subject areas of environment (both biotic and abiotic), contaminant loads, and commercial or recreational exploitation, each of which requires a simple 'Yes' or 'No' response. A documented rationale is provided for each question, as is information to assist in answering the question, if necessary. Upon completion, an assessment is made of the relative health of the ecosystem based on an objective evaluation of the user's responses, and optional printouts provide additional detail of stress symptoms and data inadequacies.

Development of the Dichotomous Key followed an evolutionary process. Early versions, while somewhat rudimentary and incomplete, nevertheless generated substantial enthusiasm amongst various managers and scientists within the Great Lakes community. Several updates or modifications to the Key ensued as feedback was obtained from new users. In order to accelerate the feedback process, an IJC/GLFC Lake Trout Dichotomous Key Workshop was sponsored in Windsor, Ontario, March 11-15, 1985 (Appendix A). Twenty scientists and managers from the United States and Canada, most from the Great Lakes region, collaborated in the generation of new insightful questions and accompanying rationales for the Dichotomous Key; the provision and documentation of appropriate data for use in the Key; and the development of a revised format for presentation. Appendix B lists the array of questions used in the Lake Superior version of the Key, along with the rationale for, and current value ('Help' screen) for the answer to each one. The numbers in parentheses appended to these statements provide reference to supportive literature citations as listed in Appendix C .

RATIONALE FOR THE LAKE TROUT DICHOTOMOUS KEY

The essential ingredient for understanding the Dichotomous Key *modus operandi,* is the concept of the Fry-Hutchinsonian niche (Kerr and Ryder 1977). Basically, this is the abstract hypervolume that is generated by assigning a dimension to each factor that affects an organism's survival. More simply stated, each organism has an inherent, genetically-determined scope for activity along many abiotic dimensions such as heat, nutrients, oxygen and light, as well as behavioral responses along several biotic axes such as reproduction, feeding or competition. Fundamental or potential niche, therefore, may be equated to genotype (Ryder et al. 1981), that is, the potential scope for activity if an organism (hypothetically) has no exogenous environmental constraints of any kind.

However, an organism taken within the context of its environment is behaviorally and metabolically constrained along most of its fundamental niche dimensions, due to various natural, environmental controls. Consequently, its niche envelope shrinks along these dimensions in proportion to the degree of external constraint (Figure 1). This condition represents the phenotypic response of the organism to exogenous stresses, which usually include both those that are naturally derived and those that are of anthropogenic origin. This substantially reduced niche envelope becomes the realized or operational niche which is essentially the fundamental or potential niche as constrained by all environmental stresses. In Figure 2, we have separated stresses derived from human intervention from those that are naturally caused in order to show how realized niche is further constrained by cultural stresses superposed onto a suite of natural background stresses. Ultimately, severe environmental intrusion along one or more niche dimensions may reduce an organism's metabolic or behavioral activities to the extreme level where death ensues. Less obvious, but nonetheless critical, are sublethal effects due to slight or intermittant intrusion of the environment on one or more niche dimensions, which may, for example, lead to reproductive failure.

Consequently, the niche concept forms the basis of the Lake Trout Dichotomous Key, in that the questions asked are designed to detect shifts in the boundaries of the lake trout's realized niche as a result of anthropogenic interventions. The outer limits to a substantial number of these niche boundaries have been previously documented and synthesized (see Martin and Olver 1980), and a subsequent expanded listing published in the lake trout bibliography of Olver and Martin (1984).

Niche boundary conditions are usually expressed as numbers, ratios or percentages, when these values are known. Because it is probably not wise to manage an ecosystem close to its ecological limits, all values stated in the queries of the Dichotomous Key are intended to be somewhat conservative, providing at least a minimal safety margin. Other questions may be purely qualitative, requiring judgmental answers. Some questions infer a quantifiable answer, but as requisite data may be lacking they also require a judgmental decision. These latter questions most often relate to interactions of the lake trout with other biotic components of the cold-water community.

Occasionally, upper and lower boundaries must be described for certain niche dimensions. This condition occurs when the normal range of an environmental variable over the course of four seasons assumes the form of an optimality curve (e.g. Fig. 3A) in terms of the response of the lake trout. In such instances the quantified variable may be expressed as an upper and lower limit, or alternatively, as a deviation from the optimal level. Other questions will deal with only single-ended tests relating to either an upper or a lower stress limit (Fig. 3B). These conditions result when the levels experienced, including

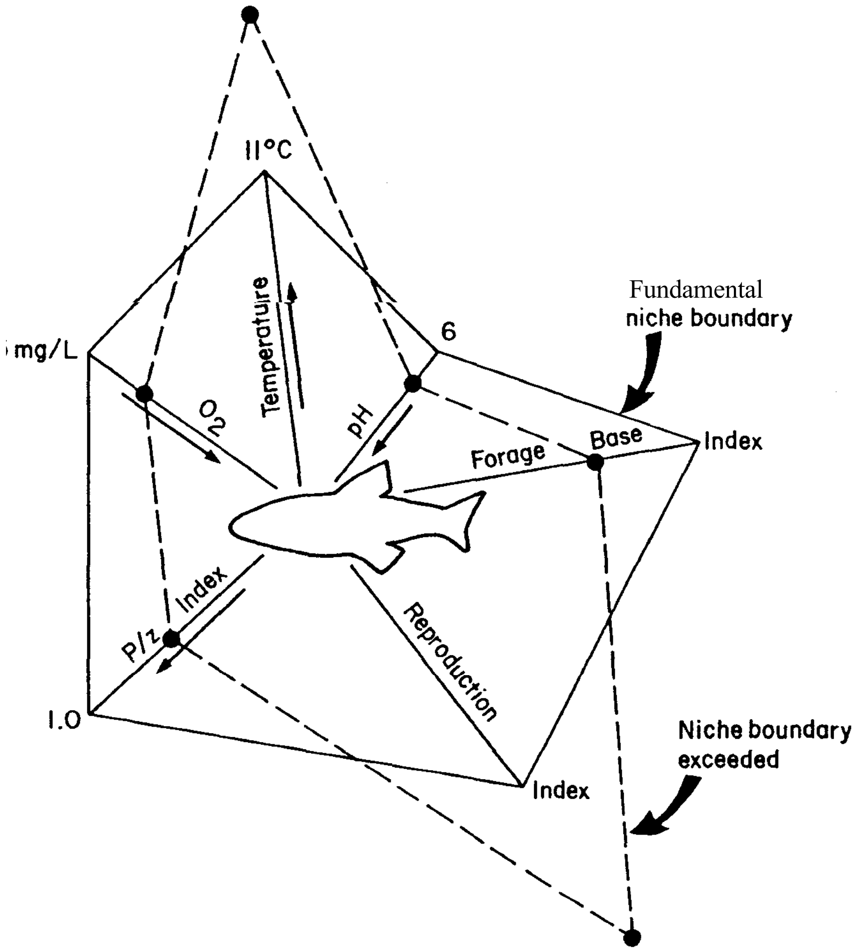


FIG. I. Scope for activity of the lake trout according to its fundamental niche boundaries (genotype) depicted in two dimensions (solid line). Environmental variable values with outward-pointing arrows are optimum levels (P/z, temperature), while inward-pointing arrows indicate minimum levels tolerated (O_2, pH). Forage base and reproduction are relative, with their index values shown as representative of the biotic portion of environment that intrudes on the lake trout's fundamental niche envelope.

the anthropogenic inputs, do not exceed those boundary conditions easily tolerated by lake trout.

Multidimensional response surfaces for lake trout, as they interact with the

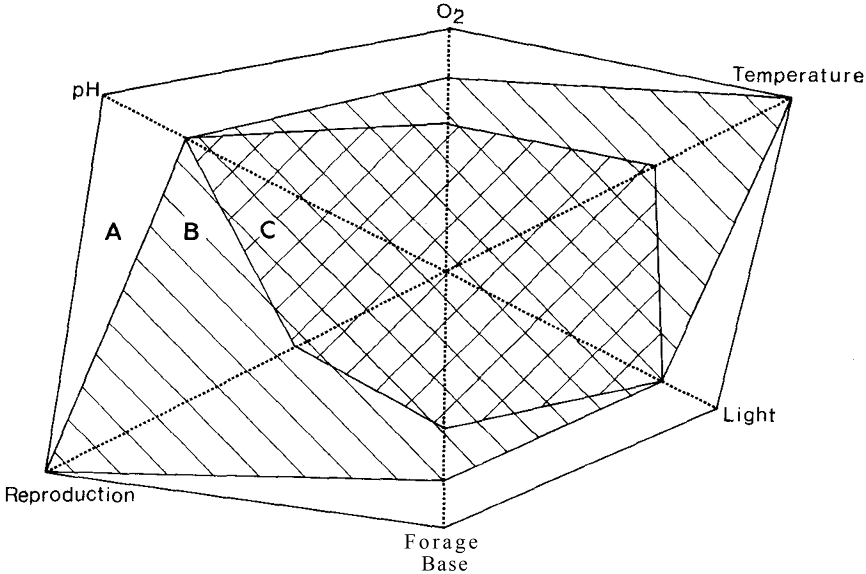
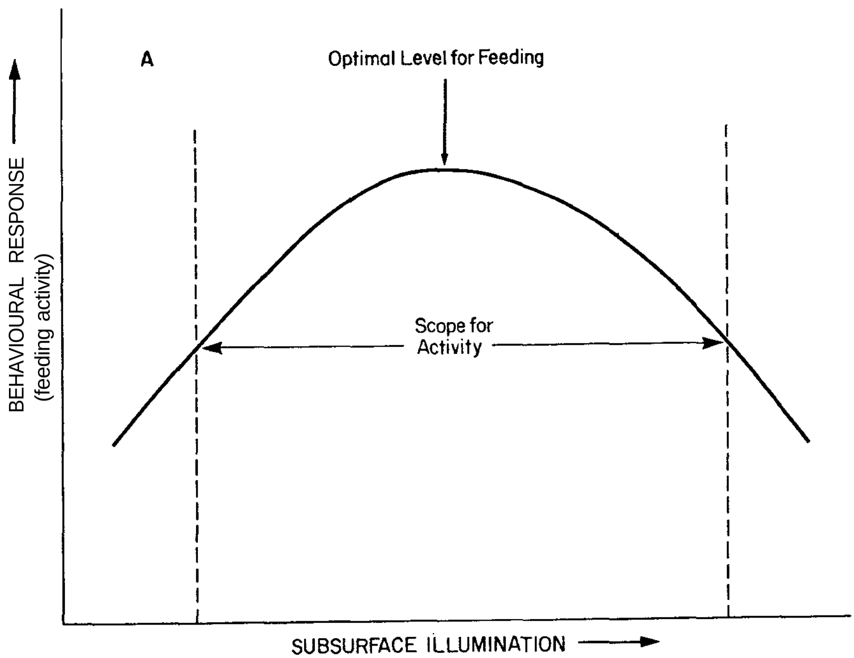
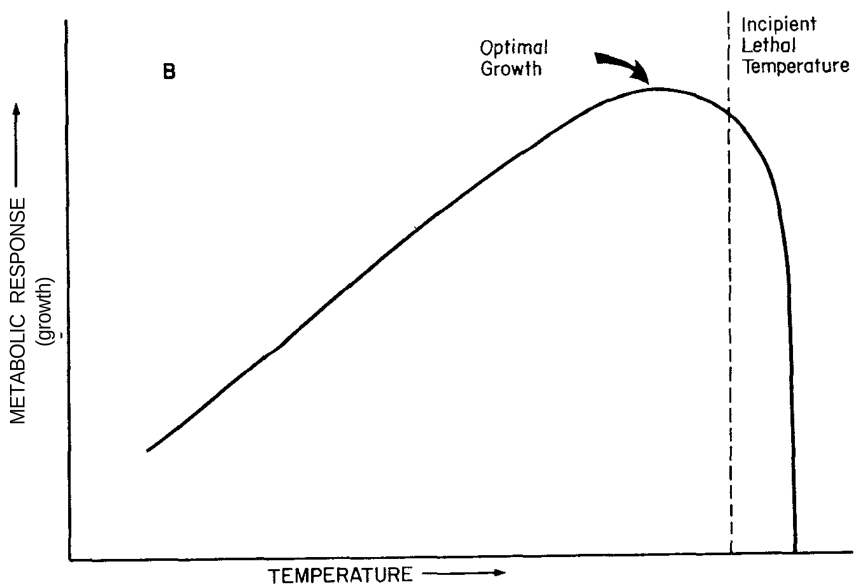


FIG. 2. Two-dimensional representation of: A-Fundamental (potential) niche of the lake trout as determined by its genotype; B-realized (operational) niche which is the fundamental niche as constrained by natural environmental controls, including other biota; and C-realized niche, as further constrained by anthropogenic modifications to the environment, such as contaminant inputs or physical alterations. In this example, the organism is at the epicenter of the niche envelope, and several of the dimensions shown have been severely constrained.

environment, have been broken down into unidimensional response curves for use in the Dichotomous Key. Response curves resulting from exposure of lake trout to one or more environmental stresses may assume a variety of forms (e.g. Regier and Henderson 1973). Accordingly, Dichotomous Key queries will attempt to ask appropriate questions relative to the response of the lake trout to any particular stress. In some instances, such as in the case of dissolved oxygen, inquiry will be made only about the lowest level of tolerance (Fig. 3C), as stress due to supersaturation of dissolved oxygen is infrequent in a natural lake regimen.

For temperature, incipient upper, lower, and perhaps optimal values may be of interest in the consideration of the lake trout's survivability, growth, and reproduction. However, only incipient upper lethal temperatures will normally be considered where temperature stresses are concerned. The Dichotomous Key attempts to describe the simplest boundary condition for any stress, regardless of whether or not the response of the lake trout to that particular stress is linear, exponential, assumes the shape of an optimality curve, or has a threshold value. Further details pertaining to the conceptual aspects of this approach may be found in Fry (1947).


A
Optimal Level for Feeding
Scope for Activity
BEHAVIOURAL RESPONSE
(feeding activity)
SUBSURFACE ILLUMINATION


B
Optimal Growth
Incipient Lethal Temperature
METABOLIC RESPONSE
(growth)
TEMPERATURE

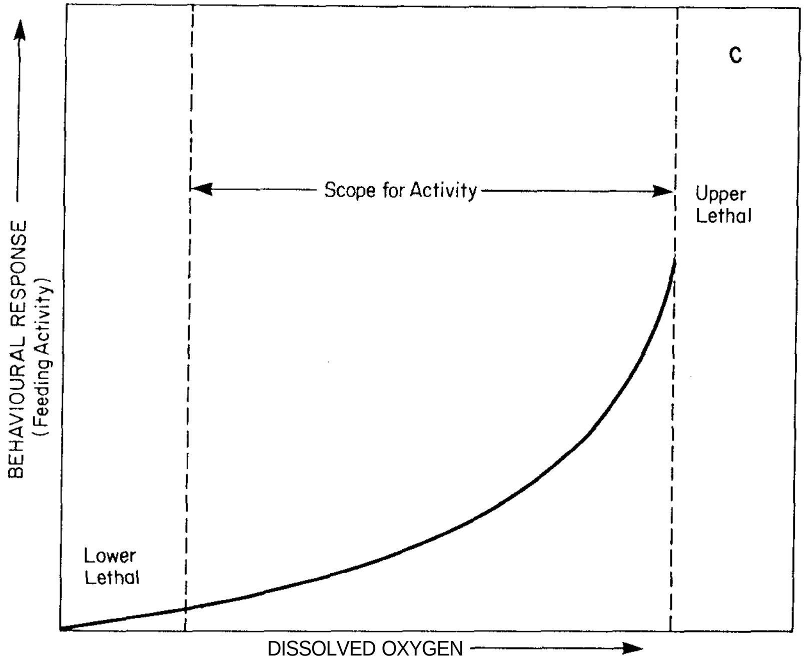


FIG. 3. Some examples of gross stress-response relationships between the lake trout and its natural environment. A-For subsurface illumination, intermediate light levels provide the best conditions for feeding; B-the incipient lethal temperature represents a threshold which results in complete mortality when exceeded; optimal growth rates occur at temperatures proximate to lethal temperature; C-dissolved oxygen concentrations become stressful and eventually lethal below critical levels; supersaturation of O_2 is sufficiently rare in nature as to prelude consideration.

USE AND OPERATION OF THE DICHOTOMOUS KEY

The Dichotomous Key may be considered to be a simple 'Expert System', in the terminology of computer science. It represents a method for the transference of knowledge from experts to non-experts for the purpose of diagnosis and problem solving. Technical knowledge of computers is not required to use the system effectively. Once the software for the Dichotomous Key has been loaded into the computer, the user simply responds to screen prompts. The program is completely menu-driven, and the user need only press **the indicated computer keys to proceed through the Key. A simplistic flowchart** (Fig. 4) illustrates program progression.

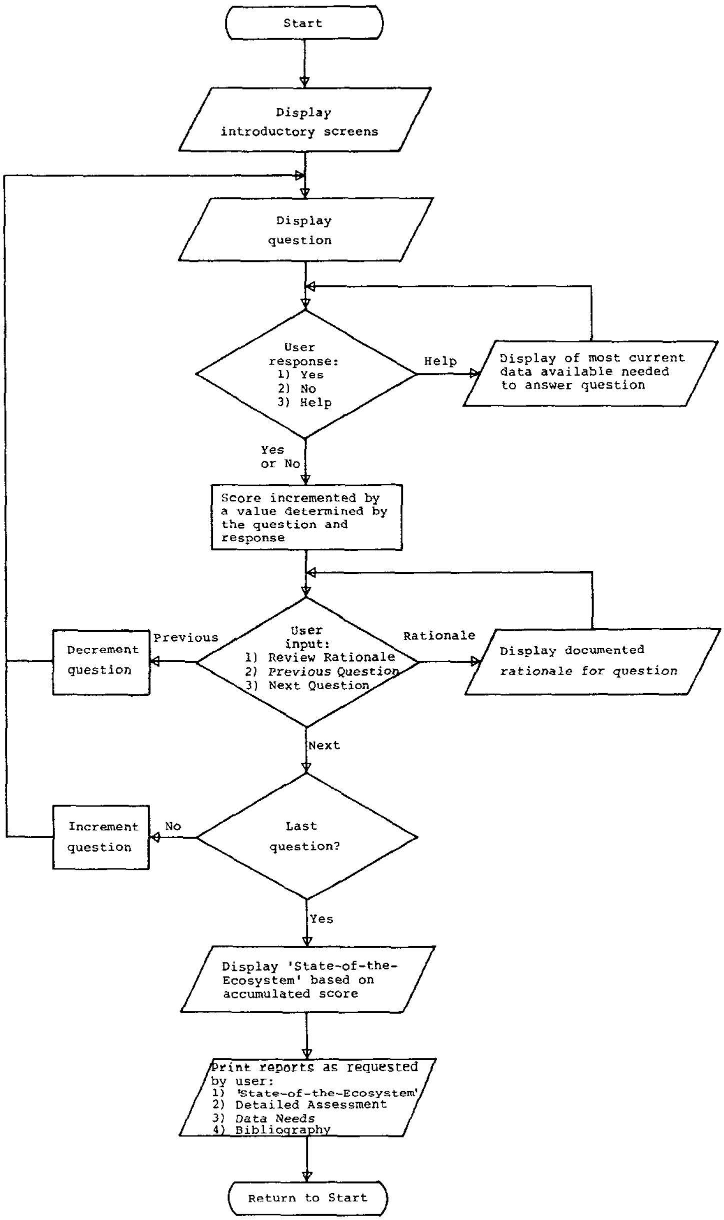


FIG. 4. A simplified flow-chart which illustrates the general operation of the Dichotomous Key. The format of the Key is not static, but is expected to continuously evolve as our knowledge base expands.

The user is first requested to identify himself and record the current date. Three options are then presented: 1) branch to the introductory screens, 2) branch to the 'Utilities' menu, or 3) begin the Key. The introductory screens provide reference documentation, acknowledgments, and a brief description of the form and function of the Key. The 'Utilities' menu allows the user to: customize the Key by defining certain system parameters; print out a bibliography of the references for the rationale and current value of each question; or alternatively, list or clear the 'scores' accumulated from previous runs through the Key.

The main body of the Key consists of a series of questions, sequentially displayed, each of which must be answered by a 'Yes' or a 'No' before proceeding to the next question. Where the answer to the question is not known to the user, a 'Help' screen may be requested which displays current data on the subject as required to answer the question. In subject areas where precise quantitative information is currently lacking, the 'Help' screen lists data for other lakes, comparable in certain respects, which will assist the user in making a decision as to the current condition in Lake Superior. The 'Help' feature should encourage the informed layman to use the Key, since even with insufficient data at hand to answer a particular question, a reasonable conclusion regarding the state of the ecosystem may still be attained.

Once a question has been answered, the user has access to a 'Rationale' option. This will provide a documented rationale for the question just answered, as previously determined by concensus at the Lake Trout Dichotomous Key Workshop. Following presentation of the rationale, a user may review and modify the answer to the current or previous question, or alternatively, proceed to the next question. This process is repeated until all questions have been answered, at which time the user's 'score' is assessed to provide a 'state-of-the-ecosystem' report, which describes the relative well-being of the ecosystem.

The score is determined by the user's response to the questions presented. A negative response results in the score being incremented by a value which is assigned to each question. The assigned value relates to the perceived degree of ecosystem degradation implied by the question. Questions designed to detect stresses which result in reproductive failure, the demise of stocks, or a major reduction in abundance, have been assigned a value of 3. Questions which detect altered population characteristics, but of lesser severity, such as stress-related changes in age, growth, or abundance, or habitat alterations which may affect reproductive potential, have been assigned a value of 2. Finally, questions which detect stresses perceived to have minimal impact on lake trout, such as slight deviations in water quality from the optima, or qualitative changes in the forage base, have been assigned a value of 1. One of three 'state-of-the-ecosystem' reports is presented, as determined by the user's accumulated score, which is subtracted from the maximum score possible and expressed as a percentage. A score of 50% or less would imply a severly degraded ecosystem. Similarly, a score ranging from 51% to 80% would suggest moderate degradation, while a score exceeding 80% would indicate only slight ecosystem degradation. A state of 'perfect' ecosystem health would be evident if the user responded positively to each question, and hence generated a score of 100%.

In addition to the presentation of a 'state-of-the-ecosystem' report following completion of the Dichotomous Key, actual scores from the current and previous runs through the Key are provided. Comparisons with past results can thus be made following reiteration of the program. In these instances, answers to the questions will change as new data become available, or as the user gains a better understanding of the process. Optional reports include a detailed listing of ecosystem attributes which adversely affect lake trout (as flagged by negative responses to questions), and are therefore indicators of ecosystem degradation. This printout will often expose a previously undetected stress, or place emphasis on one that was not thought to be critical. Accordingly, the user will become aware of areas of concern for future rehabilitation initiatives. An additional printout lists questions where 'Help' was required, indicating data deficiencies, which may imply the need for further research. The option of printing out the documentation of the rationale and current value for each question is also available to the user.

The Dichotomous Key, as described, utilizes the lake trout as an indicator organism to assess the health of the Lake Superior ecosystem. This is a continually evolving program, however, with future expansion and refinement expected as our knowledge base grows. It is expected that future versions of the Key will be directed to each of the Great Lakes, and will utilize other indicators as appropriate. Its greatest ultimate benefit may be derived from future user interaction, based on a firmer understanding of aquatic ecosystem form and function. We encourage future users, be they ecosystem managers or laymen, to provide feedback according to their individual perceptions or expertise.

ACKNOWLEDGMENTS

We thank all participants (Appendix A) of the Lake Trout Dichotomous Key Workshop held in Windsor, March 11-15, 1985, for their conscientious and expert contributions. However, we hold none of them responsible for our interpretations of their valuable inputs.

We are grateful for the continuing moral and financial support of the International Joint Commission (IJC) and the Great Lakes Fishery Commission (GLFC) through their Science Advisory Board (SAB) and Board of Technical Experts (BOTE) respectively. The Aquatic Ecosystem Objectives Committee of SAB chaired by W. M. J. Strachan provided the launching pad for this initiative, and subsequently has been strongly supportive of it in each of its various stages. We owe a debt of gratitude to C. M. Fetterolf, Jr., and R. L. Eshenroder of the GLFC Secretariat for their continuing interest and support, as well as to A. H. Watson and several support staff of IJC for handling the arrangements of the Lake Trout Dichotomous Key Workshop which contributed new and vital information towards further development of the Key. The Dichotomous Key is the culmination of group interaction at the workshop.

We are grateful to B. A. Krishka for his major contribution, which, among other things, included converting the Dichotomous Key computer program (originally designed on a Commodore system) to a program compatible with the Apple II + , IIe and IIc systems. Jeane Pesendorfer provided technical support throughout the development phase of the Dichotomous Key. Yvon Gagne (IJC) supplied the excellent line drawings and Christine Rantala typed through several drafts of the manuscript. We owe a debt of gratitude to all for their individual contributions. Finally, profuse thanks are due to several constructive reviewers of this manuscript and the Dichotomous Key including Dr. F. W. H. Beamish, Mr. B. H. Johnson, Dr. C. K. Minns, and Dr. W. M. J. Strachan.

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APPENDIX A

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APPENDIX B

List of questions, and the rationale and current status for each, that comprise the Lake Superior version of the Dichotomous Key. Questions have been grouped into four major subject areas.

EXPLOITATION AND PRODUCTION

QUESTION 1:
Is the annual forage fish harvest (i.e. combined yields of lake herring, rainbow smelt and chubs) less than 0.50 $kg.ha^{-1}$?

RATIONALE:
Based on long-term harvest records (1899-1930), the mean annual forage fish harvest equalled 0.50 $kg.ha^{-1}$. A greater harvest is probably excessive and may lead to a decline in the lake trout forage base (3).

CURRENT STATUS:
Catch records (1968-1977) for the major forage fish species (rainbow smelt, lake herring, chubs) in Lake Superior indicated a mean annual forage fish harvest of 0.40 $kg.ha.^{-1}$. The harvest was 0.16 $kg.ha^{-1}$ in 1982 and 0.13 $kg.ha^{-1}$ in 1983 (3,25,27).

QUESTION 2:
Is the assemblage of forage fish (species and phenotypic stocks) as diverse as during the early 1900's?

RATIONALE:
A less diverse forage fish base reduces community stability and does not maximize use of the resources. Overexploitation of various coregonine species through the mid-1900's contributed to a reduction in the forage base diversity (40,43,67).

CURRENT STATUS:
The present assemblage of forage fish (species and phenotypic stocks) for Lake Superior is less diverse than that of the early 1900's. While rainbow smelt and alewives are recent invaders, several of the chubs are commercially extinct (40,42,43).

QUESTION 3:
Is the total annual harvest of all salmonines less than 0.24 $kg.ha^{-1}$?

RATIONALE:
Long-term harvests of lake trout (1908-1949) were fairly constant at about 2 million kg or 0.24 $kg.ha^{-1}$. This level of harvest appeared near the maximum that could be sustained by trout stocks in the absence of sea lamprey predation (32,58).

CURRENT STATUS:
Lake trout and Pacific salmon harvests for Lake Superior in 1983 total about 389,000 kg or 0.047 $kg.ha^{-1}$. The 1982 harvest was 371,000 kg or 0.045 $kg.ha^{-1}$ (25,27).

QUESTION 4:
Do lake trout use the majority of the historical spawning and feeding habitats?

RATIONALE:
In the past, lake trout consisted of diversified stocks using many different spawning habitats and food resources. The demise of some lake trout stocks altered use patterns of these habitats (16,22,42,43).

CURRENT STATUS:
Many of the historical spawning and feeding habitats are currently unused due to the apparent demise of a number of lake trout stocks (22,23,42).

QUESTION 5:
Are the number of phenotypic lake trout stocks increasing to historic levels?

RATIONALE:
The number of phenotypic lake trout stocks must be relatively high to optimize resource utilization. During the early 1900's, 12 stocks were extant while only 2 stocks remained by 1960 (17,22,67).

CURRENT STATUS:
The number of phenotypic lake trout stocks was reduced from 12 (early 1900's) to 2 by 1960. Brown trout and four species of Pacific salmon recently established may play functionally similar roles as some extinct lake trout stocks (12,37,42,77).

QUESTION 6:
Is the ratio of all management costs (sea lamprey control, stocking, enforcement, etc.) to net societal benefit (economic, cultural, etc.) decreasing for the Lake Superior fisheries?

RATIONALE:
Economic analysis of the Great Lakes is in its infancy, however simulation modelling should be used to illustrate the effects of management strategy changes on the cost-benefit ratio to ultimately increase net benefits (75).

CURRENT STATUS:
Preliminary estimates of the cost-benefit ratio for the Great Lakes fisheries were 1:15 in 1979. This ratio is apparently not decreasing for Lake Superior (75,90).

QUESTION 7:
Is the degree of dependency on artificial control measures for sea lamprey decreasing?

RATIONALE:
Complete eradication of sea lamprey is improbable. As a harmonic fish community redevelops in Lake Superior, internal regulation will negate the need for artificial control (41,72).

CURRENT STATUS:
Sea lamprey populations continue to be held in check through a standard control program. There is no indication that a reduction in artificial control will be possible in the near future (86).

QUESTION 8:
Is the total annual mortality rate (fishing plus natural) for lake trout less than 0.5 (50%)?

RATIONALE:
A total annual mortality rate for lake trout of 50% appears to represent the maximum that can be sustained without adversely affecting yields (29).

CURRENT STATUS:
Total annual mortality rates (1980-1983) for Lake Superior lake trout range from 42% to 77% depending on the area, but are well above 50% for most areas in both U.S. and Canadian waters (57).

QUESTION 9:
Do mixed age classes of lake trout above age X for males and age XI for females constitute more than 20% of the adult standing stocks by weight?

RATIONALE:
If the population consists of too few older age classes, the possibility of population collapse due to overexploitation or other stress is increased (21).

CURRENT STATUS:
Mixed age classes of lake trout above age X (males) and age XI (females) currently constitute less than 20% of adult standing stocks in Lake Superior (87,89).

QUESTION 10:
Do standing stocks (biomass) of lake trout of size range l-10 kg constitute at least 15% of the biomass of the principal forage species of size range l-1000 g?

RATIONALE:
Assuming a flat, slightly negative size spectrum characteristic of a balanced system, lake trout biomass should be 30% that of their forage within these size ranges. Reducing this ratio (through fishing) to 15% or less may be catastrophic **(6,81).**

CURRENT STATUS:
While size structure relationships between lake trout and their forage have not been compiled specifically for Lake Superior, it has been predicted that the biomass ratio for these two groups exceeds 15% in Lake Ontario (6).

QUESTION 11:
Is the age of first reproduction of lean female lake trout greater than V but less than IX?

RATIONALE:
The age of first reproduction traditionally ranged from V to IX in Lake Superior. An earlier age may indicate a compensatory response to exploitation while a later age implies very slow growth (43).

CURRENT STATUS:
Currently, the age of first reproduction is very close to, but less than IX for lean female lake trout in Lake Superior (48,49).

QUESTION 12:
Is Abrosov's 't' value greater than 2.0 years for lake trout (mean age of catch from standard sampling gear minus age of first maturity)?

RATIONALE:
The Abrosov index provides a measure of the average reproductive life span per individual. A value of less than 2.0 years may imply population instability and is typically caused by excessive removal of older adults (1,56).

CURRENT STATUS:
Mean age of lake trout from the commercial catch in the Canadian waters of Lake Superior in 1983 and 1984 was 8.1 years. The age of first maturity is approximately 9 years (48).

ENVIRONMENTAL (BIOTICS)

QUESTION 1:
Do rainbow smelt and/or alewives constitute less than 40% (+/-10%) of the diet by volume of mature lake trout?

RATIONALE:
Thiamin-related dietary problems may arise and reproductive efficiency may be affected if diet consists largely of exotic species such as rainbow smelt or alewife. Lake trout distribution also changes when feeding on exotic species (18).

CURRENT STATUS:
In Lake Superior, adult lake trout are feeding almost exclusively on rainbow smelt in inshore areas. Other forage species (e.g. lake herring, sculpins) may constitute most of the adult lake trout diet in the offshore areas (11,70).

QUESTION 2:
Do Mysis *relicta* and *Pontoporeia hoyi* collectively comprise over 80% of the diet by volume of lake trout under 200 mm in length in offshore waters?

RATIONALE:
Crustaceans (largely *Mysis relicta* and *Pontoporeia hoyi)* traditionally comprised over 80% of the diet by volume of young lake trout in Lake Superior. Diet changes may reflect a restructuring of the zooplankton or benthos community (13,15).

CURRENT STATUS:
In shallow inshore areas, chironomids make up nearly 80% of the diet by volume of YOY lake trout. As habitat changes to deeper offshore waters, however, it is suspected that crustaceans are the most abundant prey of appropriate size (74).

QUESTION *3:*

Do sculpins (Myoxocephalus sp., *Cottus* sp.) constitute at least 10% by volume of all food ingested by adult lake trout?

RATIONALE:

Adult sculpins are extremely sensitive to cultural intervention and their absence in lake trout diet might indicate a degraded habitat. Sculpins traditionally comprised about 10% of the lake trout diet (13).

CURRENT STATUS:

Sculpins probably constitute 10% (by volume) or more of the diet of adult lake trout in offshore waters, but do not contribute this much inshore (87).

QUESTION *4:*

Do fish comprise more than 50% of diet by volume for lean lake trout 50-60 cm in length?

RATIONALE:

Lean lake trout 50-60 cm in length are largely piscivorous with fish traditionally comprising over 90% of diet by volume. If large lake trout instead feed mainly on smaller particle sizes, a predator-prey imbalance is indicated (13,39).

CURRENT STATUS:

Lake trout in the 50-60 cm size range feed almost exclusively on fish in both inshore and offshore areas (11).

QUESTION *5:*

Is the lake trout yield 15% (+/-5%) of the principal forage fish yield (deep and shallow water ciscoes, rainbow smelt)?

RATIONALE:

A normal range of conversion efficiency between two adjacent trophic levels in trophic dynamic systems lies between 10% and 20%. Yield is proportional to production, therefore conversion ratios will be similar (44).

CURRENT STATUS:

Lake trout commercial harvest equalled 28% of the forage fish harvest in 1982 and was 37% for 1983 (25,27).

QUESTION 6:
For logarithmically equal size classes of organisms from phytoplankton to large fish, is a plot of log biomass vs log body weight relatively linear with a slope not markedly different from zero?

RATIONALE:
The expected plot of log biomass vs log body weight for logarithmically equal size classes of organisms from a healthy (balanced) ecosystem would be continuous with a slope of approximately -0.02 (6).

CURRENT STATUS:
Data are not yet available to calculate a predicted slope across the size spectrum for Lake Superior, however a slope of -0.02 has been predicted for Lake Ontario (6,81).

QUESTION 7:
Are standing stocks of burbot greater than 10% of those of lake trout?

RATIONALE:
Low standing stocks of burbot may reflect a benthic community which is under stress. Low burbot biomass may also indicate stress due to sea lamprey predation (19,85).

CURRENT STATUS:
Burbot standing stocks are suspected to be much greater than 10% of lake trout standing stocks at the west end of Lake Superior and would average more than 10% across the entire lake (89).

QUESTION 8:
Is the average length of age VIII lean lake trout between 50 cm and 75 cm?

RATIONALE:
Growth rates slower than the traditional averages imply stress due to a collapsing forage base or water quality degradation. Rapid growth rates may indicate overexploitation or high levels of sea lamprey predation (15,29,59,60).

CURRENT STATUS:
The average length of age VIII lean lake trout is 63 cm for stocked fish. Native fish average 55 cm for inshore areas (i.e. Thunder Bay) and 60 cm for U.S. waters (10,89).

QUESTION 9:
Is the mean condition factor (standard metric k) above 0.90 for lake trout greater than 50 cm?

RATIONALE:
Lake trout with k-factors less than 0.90 may have an inadequate forage base, demonstrate inordinately high competition for food, or be subjected to an anthropogenic stress inimical to a normal growth regime (14,51).

CURRENT STATUS:
An exact value is not available, but the mean condition factor likely approximates 1 for Lake Superior lake trout (89).

QUESTION 10:
Are native juvenile lake trout demonstrating increased abundance as indicated by catch per unit effort (CUE) using standard assessment gear?

RATIONALE:
A decrease in the CUE of native juvenile lake trout would suggest that increased recruitment of natives is not occurring and the dependency on stocked fish must continue (26).

CURRENT STATUS:
Juvenile abundance data (1973-1983) for Minnesota waters of Lake Superior reported a low CUE of I native per 1000 m of gill net in 1976. Native juvenile abundance has since increased to 23 natives per 1000 m in 1983 (26).

QUESTION 11:
Has the general perception of the aesthetic value of the ecosystem improved?

RATIONALE:
Rehabilitated ecosystems show marked improvement in water quality and the re-establishment of natural communities. They are more aesthetically pleasing, in terms of water clarity and biota, than are degraded ecosystems (55,61,73).

CURRENT STATUS:
Lake Superior water quality continues to be slightly to moderately degraded, particularly in the nearshore littoral areas and near large river deltas. Aquatic communities are largely natural with some dominant exotic components.

ENVIRONMENTAL (ABIOTICS)

QUESTION 1:
During August and September, is the mean epilimnetic temperature less than 13°C?

RATIONALE:
Lake trout generally occupy water ranging from 5-13°C and were once common in mid-lake surface waters in Lake Superior. An increase in lake temperature, as a result of altered land use patterns, may restrict their distribution (51,53).

CURRENT STATUS:
Synoptic surveys carried out between 1964 and 1973 indicate that the maximum ‘lakewide surface temperature seldom exceeds 14°C and that mean epilimnetic temperatures during August and September would be much less than 13°C (5).

QUESTION 2:
Are water temperatures on spawning beds for fall shoal spawning lake trout less than 10°C during the period of spawning?

RATIONALE:
Surveys of inland lake trout lakes indicate that while water temperatures range from 5-13°C they are generally less than 10°C during the fall spawning period (51).

CURRENT STATUS:
Bottom water temperatures for Lake Superior prior to the onset of spawning (late October) would be approximately 4°C as recorded in a 1983 survey (33).

QUESTION 3:
Do mean water temperatures remain less than 3°C on inshore and river spawning beds during the period of egg incubation for fall spawning lake trout?

RATIONALE:
Temperature surveys of the spawning beds used by fall spawning lake trout indicate average water temperatures of 3°C or less during the period of egg incubation (51,85).

CURRENT STATUS:
Synoptic temperature surveys for Lake Superior (1964-1973) indicate that average water temperatures are less than 3°C from late December to mid-June, although isolated exceptions are possible (5,85).

QUESTION 4:
During late summer, is the hypolimnetic dissolved oxygen concentration at saturation?

RATIONALE:
Due to its ultra-oligotrophic nature, hypolimnetic dissolved oxygen concentrations in Lake Superior have historically been at saturation (4,78).

CURRENT STATUS:
Lake Superior hypolimnetic dissolved oxygen concentrations continue to represent 100% saturation, as demonstrated in an October 1983 survey (33).

QUESTION 5:
During incubation, is the interstitial dissolved oxygen concentration on the spawning beds at 50% saturation or higher for water temperatures of 7°C or less?

RATIONALE:
During incubation, an interstitial dissolved oxygen concentration of less than 50% saturation (at 7°C) leads to poor survival and impaired development of lake trout larvae (8).

CURRENT STATUS:
Current data are not available for Lake Superior. Lake Huron interstitial waters were at 50% saturation in February 1985 (88).

QUESTION 6:
Is the mean surface pH within the range 7.6-8.3 for Lake Superior?

RATIONALE:
A mean surface pH of 7.6-8.3 is within the traditional range of surface pH for Lake Superior waters (2,24,78).

CURRENT STATUS:
Lake Superior surface pH ranged from 7.8 to 8.3 in 1973 and averaged 8.0 for the entire year (78).

QUESTION 7:

During spring ice melt, does the interstitial pH on the spawning beds exceed 5.0 and is the inorganic Al concentration less than 25 $\mu g.l^{-1}$?

RATIONALE:

Sac fry are subjected to stress and mortality when interstitial pH is below 5.0 and inorganic Al exceeds 25 $\mu g.l^{-1}$ during spring ice melt. Interstitial waters maintain higher pH and Al levels than ambient waters (28).

CURRENT STATUS:

Northeastern Lake Superior tributaries in the vicinity of known lake trout spawning areas reveal pH minima slightly above 5.0 during spring runoff. Al concentrations are not known (38).

QUESTION 8:

Are concentrations of un-ionized ammonia (NH_3) in the water column less than 30 $\mu g.l^{-1}$?

RATIONALE:

Un-ionized ammonia (NH_3) concentrations exceeding 30 pg.1 $^{-1}$ have been demonstrated in the laboratory to affect growth of Pacific salmon (9).

CURRENT STATUS:

The mean un-ionized ammonia (NH_3) concentration for Lake Superior (1969-1980) is 0.06 $\mu g.l^{-1}$ based on pH=7.6 and $t = 10°C$. The allowable concentration has been exceeded at the mouths of tributaries of the Great Lakes (9).

QUESTION 9:

Is the ratio of lakewide total spring phosphorus ($\mu g.l^{-1}$) to mean depth (m) less than 1.0?

RATIONALE:

A ratio of total spring phosphorus ($\mu g.l^{-1}$) to mean depth (m) exceeding 1.0 may reflect inhospitable temperature and/or oxygen regimes for lake trout (65).

CURRENT STATUS:

Based on a current (1983) spring phosphorus value of 3.1 pg.1 $^{-1}$, Lake Superior has a p:z ratio of 0.02 (33).

QUESTION 10:
Does the mean photic zone depth (depth reached by 1% to the surface irradiance, or approximately 2.7 x Secchi depth) exceed 25 m in the offshore waters (May-November)?

RATIONALE:
Mean photic zone depths exceeding 25 m in offshore areas of Lake Superior were recorded during a 1973 survey. Similar or greater depths represent historic ultra-oligotrophic conditions when a greater diversity of lake trout stocks occurred (69).

CURRENT STATUS:
The photic zone depth exceeded 30 m for Lake Superior offshore waters in October 1983 (33).

QUESTION 11:
Does the mean photic zone depth (depth reached by 1% of the surface irradiance, or approximately 2.7 x Secchi depth) exceed 10 m in nearshore lake trout spawning areas (May-November)?

RATIONALE:
Mean photic zone depths exceed 10 m in nearshore areas where known spawning grounds occur (e.g. Thunder Bay), while transparency is less in other areas (e.g. southern Duluth Bay) where lake trout spawning is non-existent (23,69).

CURRENT STATUS:
The mean photic zone depth is less than 10 m near the mouths of large turbid rivers and in some bays (e.g. Duluth, Black), but is commonly greater than 10 m in other nearshore areas (23,69).

QUESTION 12:
Have lake trout spawning areas remained relatively unaffected by man’s activities (e.g. dredging) which may impede spawning or reduce egg survival?

RATIONALE:
High quality spawning shoals consist of clean gravel or rubble. Man’s activities are often detrimental to these areas, through increased siltation, substrate alteration, and other forms of disturbance (61,63,73).

CURRENT STATUS:
With local exceptions, spawning beds have not been degraded by man to any great degree in Lake Superior and remain abundant. (23).

QUESTION 13:
Is the shallow-water spawning substrate for lake trout of sufficient size (2-20 cm) and depth (greater than 15 cm) to permit infiltration of trout eggs into interstitial spaces and thus provide protection from predators?

RATIONALE:
Spawning substrate which is not within the size range of 2-20 cm and which is less than 15 cm deep does not allow egg lodging within gravel boulder interstices, and may subject the eggs to greater predation (14,45,51).

CURRENT STATUS:
While adequate substrate is not present in some sedimentary areas of the Great Lakes, material of the preferred size is abundant at required depths along the shorelines of Lake Superior (76).

QUESTION 14:
Is the available spawning substrate at depths greater than that at which the ice foot forms or ice scouring of the substrate occurs?

RATIONALE:
Spawning substrate should be free of ice scouring to prevent substrate disturbance and possible damage to developing eggs (7 1).

CURRENT STATUS:
Appropriate spawning substrate is abundant in Lake Superior over a large array of depths. Ice scouring is not considered a serious problem (71).

QUESTION 15:
Applying the toxic unit concept, is the sum of the trace metal ratios (current concentration: water quality objective) for As, Cd, Cu, Pb, Hg , Se, Ag , and Zn less than 1.0, with no one metal contributing greater than 0.2 to the sum?

RATIONALE:
Trace metal contamination exceeds safe levels when the sum of the metal ratios is greater than 1.0. If one metal contributes greater than 0.2 to the sum, it may be considered a source of toxicity (34,35).

CURRENT STATUS:
Recent data indicate the **sum of trace metal ratios to be 0.49 in offshore waters** of Lake Superior, with no individual ratio exceeding 0.2 (62).

CONTAMINANTS

QUESTION 1:
Are DDT (plus metabolites) concentrations in adult lake trout less than 1.0 $\mu g.g^{-1}$ wet weight?

RATIONALE:
DDT (plus metabolites) concentrations above 1.0 $\mu g.g^{-1}$ in fish are known to cause eggshell thinning in fish-eating birds. Concentrations above 10 $\mu g.g^{-1}$ affect reproductive success of fish through measurable sac fry mortality (7,49,80).

CURRENT STATUS:
Mean DDT (plus metabolites) concentrations in whole lake trout in Lake Superior (1983) are 0.23 $\mu g.g^{-1}$. Values of 0.61 $\mu g.g^{-1}$ (males) and 1.34 $\mu g.g^{-1}$ (females) were recorded from Marquette Harbour, Lake Superior in October 1980 (47,79).

QUESTION 2:
Is the concentration of 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) in adult lake trout less than 0.01 $ng.g^{-1}$ wet weight?

RATIONALE:
Consumptive warnings and/or a ban on sale apply in Canada and the United States for TCDD levels of 0.01 to 0.05 $ng.g^{-1}$. Higher levels (exceeding 0.30 $ng.g^{-1}$) cause teratogenic effects or acute toxicity in various fish species (30,31,54).

CURRENT STATUS:
1983 data indicate that TCDD concentrations were below the minimum limit of detection (0.01 $ng.g^{-1}$ wet weight) for Lake Superior (79).

QUESTION 3:
Is the concentration of toxaphene in adult lake trout less than 0.2 $\mu g.g^{-1}$ of fish tissue?

RATIONALE:
Concentrations of 0.2-0.4 $\mu g.g^{-1}$ may affect bone development and growth in fish, 0.4-2.4 $\mu g.g^{-1}$ may cause significant mortality in fish eggs, and concentrations above 2.4 $\mu g . g^{-1}$ may result in heavy mortality during spawning (52).

CURRENT STATUS:
Data from 1983 indicate a mean toxaphene concentration of 1.93 np,g.g-’ of fish tissue for Lake Superior lake trout (79).

QUESTION 4:

Is the concentration of total polychlorinated biphenyls (PCB) in adult lake trout less than 0.1 $\mu g.g^{-1}$ wet weight?

RATIONALE:

PCB concentrations should not exceed 0.1 $\mu g.g^{-1}$ in fish due to bioaccumulation effects within the food chain. Fish egg mortality may result if adult concentrations exceed 2.5 $\mu g.g^{-1}$ wet weight (34,36).

CURRENT STATUS:

Body burdens of PCB were 0.95 $\mu g.g^{-1}$ for male lake trout and 1.79 $\mu g.g^{-1}$ for female lake trout collected from south central Lake Superior in 1980 (47).

QUESTION 5:

Is the mixed function oxidase (MFO) activity in lake trout less than 2.0 fluorescent units per mg of post-mitochondrial supernatant protein?

RATIONALE:

Mixed function oxidase (MFO) activity levels above 2.0 fluorescent units per mg exceed mean background levels for the Great Lakes, indicating probable exposure to and metabolism of xenobiotic contaminants (46).

CURRENT STATUS:

MFO activity ranged from 0.76 to 2.94 fluorescent units per mg of post-mitochondrial supernatant protein for Lake Superior lake trout in 1983 (46).

QUESTION 6:

Is the ascorbic acid level in lake trout eggs (ripe ova) greater than 150 $\mu g.g^{-1}$ wet weight?

RATIONALE:

Reduced ascorbic acid levels (150 $\mu g.g^{-1}$ or less) in lake trout eggs (ripe ova) may be a consequence of high levels of toxicants. Values below 20 $\mu g.g^{-1}$ definitely cause reduced egg fertilization, hatchability and general survival (68,84).

CURRENT STATUS:

Current values are not available for Lake Superior. In 1983, ascorbic acid levels of 315 $\mu g.g^{-1}$ wet weight were recorded for lake trout eggs in Lake Ontario (20).

QUESTION 7:
Is the frequency of testicular constrictions in mature lake trout 12% or less?

RATIONALE:
Gonadal constrictions are suspected to be associated with contaminants. Affected male lake trout are at least one reproductive stage behind normal individuals. Naturally reproducing stocks from Lake Opeongo exhibit 12% constriction levels (64,83).

CURRENT STATUS:
Testicular constrictions were present in 33% of mature lake trout sampled near Michipicoten Island in 1981 (20).

QUESTION 8:
Is the subjective motility of lake trout sperm at the peak of spermiation greater than or equal to 7 on a scale of 1 to 10?

RATIONALE:
High contaminant burdens may affect sperm counts and motility. If the subjective motility of sperm of spawning lake trout is less than 7, a reduced rate of fertilization may result (20).

CURRENT STATUS:
Sperm motility data are not available from unstressed lakes or from Lake Superior. Based on data from 1983-85, values of 7 or higher represent successfully spawning lake trout from Lake Ontario (20).

QUESTION 9:
Are sperm counts in spawning male lake trout 10 billion per ml or higher?

RATIONALE:
High contaminant burdens may affect sperm counts and motility. Fertilization rates may be reduced if sperm counts in spawning male lake trout are less than 10 billion per ml (20).

CURRENT STATUS:
Sperm counts are lacking for Lake Superior lake trout. Samples taken from spawning lake trout in Lake Opeongo (1981) indicate sperm counts above 10 billion per ml (20).

APPENDIX C

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