A Framework for the Advancement of Aquatic Science – Lake Habitat Experiments as an Example

J.R.M. Kelso[1], R.J. Steedman[2], J.M. Gunn[3], K.E. Smokorowski[4*], N.P. Lester[5], W.G. Cole[6], C.K. Minns[7], K.H. Mills[8]

[1]*Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries & Aquatic Sciences, 1 Canal Drive, Sault Ste. Marie, Ontario, P6A 6W4 Canada*

[2]*OMNR, Centre for Northern Forest Ecosystem Research, Lakehead University, 955 Oliver Road, Thunder Bay, Ontario, P7B 5E1 Canada*

[3]*OMNR, Cooperative Freshwater Ecology Unit, Laurentian University, Sudbury, Ontario, P3E 2C6 Canada*

[4]*Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries & Aquatic Sciences, 1 Canal Drive, Sault Ste. Marie, Ontario P6A 6W4*

[5]*Ontario Ministry of Natural Resources, 300 Water Street, Peterborough, Ontario K9J 8M5*

[6]*Ontario Ministry of Natural Resources, Ontario Forest Research Institute; 1235 Queen Street East, Sault Ste. Marie, Ontario P6A 2E5*

[7]*Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries & Aquatic Sciences, P.O. Box 5050, 867 Lakeshore Road, Burlington, Ontario L7R 4A6*

[8]*Fisheries and Oceans Canada, Freshwater Institute, 501 University Crescent, Winnipeg, Manitoba R3T 2N6*

[*]*Corresponding author: e-mail: smokorowskik@dfo-mpo.gc.ca*

Abstract

Resource managers must often act to protect fisheries and fish habitat without the certainty that their actions are justified. Delivering the science needed to support and direct management decisions is a daunting exercise, likely beyond the capabilities of a single research group or management agency. This problem is exacerbated by the lack of a common framework to formulate and test important hypotheses about biotic response to aquatic habitat change. A partial solution may be provided by co-operative research networks to produce an integrated design and synthesis of quasi-independent studies within a common framework for hypothesis generation and testing. A well-designed framework should attract scientists and agencies who recognize the benefit of co-operative research. We demonstrate such an approach by using it to test hypotheses about lake fish community response to habitat change. Our framework includes a list of hypotheses, a list of treatments (i.e., habitat manipulations), an experimental design specifying the number of lakes per treatment, and advice for measuring habitat and fish parameters. Because our procedure uses 'before-after' comparisons to measure effects of habitat changes, lakes can be studied independently (and hypotheses can be tested independently) yet still contribute synergistically to the larger experiment. A 'staircase' design, ensuring that treatment effects are independent of environmental correlates such as climate variables, would be implemented, largely by default, because contributions to the design would accumulate over time. We believe this cooperative approach will improve the ability of researchers to meet the growing demands for useful, reliable aquatic science.

Keywords: experimental design, hypothesis testing, aquatic ecology

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Introduction

Reynolds (1998) offered the provocative conclusion that freshwater science is in a poor state of health, and that advances in aquatic ecology have been overshadowed by those in terrestrial ecology. Even if this conclusion is unfair, there is no doubt that aquatic scientists face a daunting challenge when formulating reliable, practical advice for aquatic resource managers. Peters (1980) modified Andrewartha and Birch's (1954) definition of ecology to stress the predictive role of science and the need to study factors that control the distribution, biomass, production, and diversity of organisms. Management intervention to ensure that production is maintained or enhanced must be based on knowledge of the factors controlling production. The easiest and least costly option to identify the critical components of production is to conduct a small scale experiment and scale this to entire ecosystems. However, there are well-known difficulties in extrapolating results from small experimental systems (e.g., bottles, aquaria, or mesocosms) to the whole-lake scale (Schindler, 1998). Although experimentation at the whole-lake scale is often prohibitively costly, these costs may be reduced when research groups and agencies operate collaboratively. Further efficiencies may be realized if a scalable research framework prevents unnecessary duplication, and optimizes practical relevance of rigorous ecosystem-scale experiments.

Too many questions and too many limitations in an agency

Aquatic habitat problems and solutions occur over a wide range of spatial and temporal scales, from meters to kilometers, often involving slow or episodic processes that are cumulative over years to decades (Imhoff et al., 1996; Lewis et al., 1996). Management interventions that affect lakes or other aquatic resources are often evaluated and regulated (i.e., licensed and permitted) individually on short time scales. However, the yardstick by which the requests for approval are gauged is the response of the fish community as a whole. For example, a request by a single cottage owner to remove nearshore rocks and trees to improve water access is gauged against the probable effect on the fish community from past and planned total cottage development for that lake. The range of temporal and spatial scales at which an ecologist might study potential impacts is daunting. The argument for ecosystem scale experiments is easy to accept in light of the complex array of process-oriented measurements that would be needed at smaller spatial and shorter temporal scales, and the interpretive ambiguities that would likely result from these small scale studies.

Resource managers want immediate answers to questions that may involve slow, cumulative ecosystem impacts. They would prefer answers expressed in terms of managed values (e.g., fish biomass, growth and fish community diversity), rather than on short-term, small-scale physical, chemical, or biological process data. Carefully controlled whole-lake experiments are probably the best way to provide these answers, but these involve the difficulty of finding replicate lakes with similar and suitable morphometry, water renewal times, chemistries, nutrient regimes, management histories, and biotic communities to use for experimental manipulation and matching control monitoring. The cost of ecosystem-scale experimental manipulation can be substantial, because the experimental treatment must be extensive enough to generate measurable responses. Where replicate treatments, reference systems, or long-term baseline measurements are not feasible, the credibility of subtle or contentious experimental findings may be reduced (Carpenter et al., 1989; Faith et al., 1991; Underwood, 1993). Researchers can increase their ability to deliver timely, useful answers to resource managers by planning and conducting complementary experiments within a structured collaborative framework. Ideally, the framework will include a variety of experimental approaches, using different spatial and temporal scales (Rassam, 2001).

The resource manager's dilemma

The costs for ecosystem restoration are high (Kelso and Hartig, 1996). These costs, and uncertainty associated with the results (e.g., Bassett, 1994; Smokorowski et al., 1998) encourage managers to adopt stringent conservation and protection measures. Cairns (1991) suggests that the science of restoration ecology is in poor condition because: 1) most actions are directed at fragments of systems rather than ecosystems, 2) the 'expanding synthesis' of Wilson (1978) has not followed the 'raw reduction' provided by scientists, 3) we have only begun to apply Bradshaw's (1996) acid test for ecology, namely that restoring ecosystems tests the state of the science of ecology, and 4) Turner's (1987) challenge, that is, to construct a system that does the same thing as another, has not been met. Restoration and rehabilitation (see Bradshaw, 1996 for definitions) initiatives for fisheries habitat usually suffer from lack of integration among the disciplines. It should therefore be no surprise that we are unable to repair ecosystems if we rehabilitate and study at inappropriate scales, fail to incorporate the disciplines needed for rehabilitation, and do not integrate these experiences into the study of ecology.

An unresolved issue for aquatic habitat managers is whether the current compensation measures for loss of fish habitat are warranted and effective. Frequently, destruction and alteration of fish habitat is authorised if the proponent agrees to enhance fish habitat elsewhere, so that there is no net habitat loss in the ecosystem. The assumptions underlying this management approach are 1) destruction of habitat causes a compensatory decrease in productive capacity (see DFO, 1986 for an explanation and application of the term) and 2) enhancement or creation of habitat elsewhere will increase productive capacity. Neither assumption may be true. At best, the 'cause-effect' relation of the amount or kind of physical habitat to fish production is poorly defined. Acceptance of the first assumption is precautionary; acceptance of the second assumption is tenuous but rejecting it would permit losses with no replacement. According to Ludwig et al. (1993), experience and a reasonable understanding of causes are insufficient to avoid misuse or destruction of natural resources.

Our 'Field of Dreams'

In ecology, even simple questions can result in demanding and costly experimental designs to provide useful answers. Due to natural variation and measurement error, several years of monitoring are required to detect large changes to fish populations. Detection and reliable diagnosis of smaller effects requires replication and additional years of study (Walters et al., 1988; Lester et al., 1996). Most scientists succumb to the realities of agency funding and seek financial support for a portion of the design. Because each research proposal is evaluated independently, and several researchers may compete for the same pot of money, the funding process fosters a fragmented, uncoordinated scientific assault on the important problems in fisheries and fish habitat management.

The alternative we propose is a 'Field of Dreams' (Kinsella, 1982) for aquatic habitat science. Like the Iowa farmer who carved a baseball field in a field of corn, our suggestion is to build our own playing field – an experimental design framework specifying the range of studies needed to test the effects of, for example, lake habitat simplification. Will the aquatic scientists of today and tomorrow come together on a field of dreams? We think so, if we build it together.

Hypotheses for habitat manipulation experiments

Ecologists frequently attempt to predict parameters such as temperature, oxygen levels, feeding rates, carbon assimilation rates, or mortality in a comprehensive model in the hope that these will eventually lead to useful predictions of biomass, production, or diversity (Peters, 1980). Instead, we opt for a more direct approach to evaluate whether a system's fish biomass and production has changed.

The scientific literature abounds with reports of the effects of environmental impacts, natural or anthropogenic, on aquatic communities (Underwood, 1989). Although often criticized for their lack of rigour, environmental impact assessments are generally concerned with prediction of environmental change (Lincoln-Smith, 1991). If impact assessment remains a part of the way we attempt to manage ecosystems, only by adopting a hierarchy of testable hypotheses will we be able to gauge whether proposed actions, developments or changes will be ecologically sustainable. The following list of questions is offered as a guide for studies that investigate a whole-lake response to changes in habitat:

- is there a change in the <u>total</u> fish biomass or production when we alter habitat?
- is there a change in the interspecific allocation of biomass or production when we alter habitat?
- is there a change in the spatial or temporal distribution of species when we alter habitat?
- is there a change in the relative contribution of habitat features to the spatial or temporal distribution of species when we alter habitat?
- at what level of disturbance of habitat will an identifiable effect occur?

If the day-to-day business of science is testing hypotheses, the above provide a framework for whole-lake studies of habitat disturbance effects.

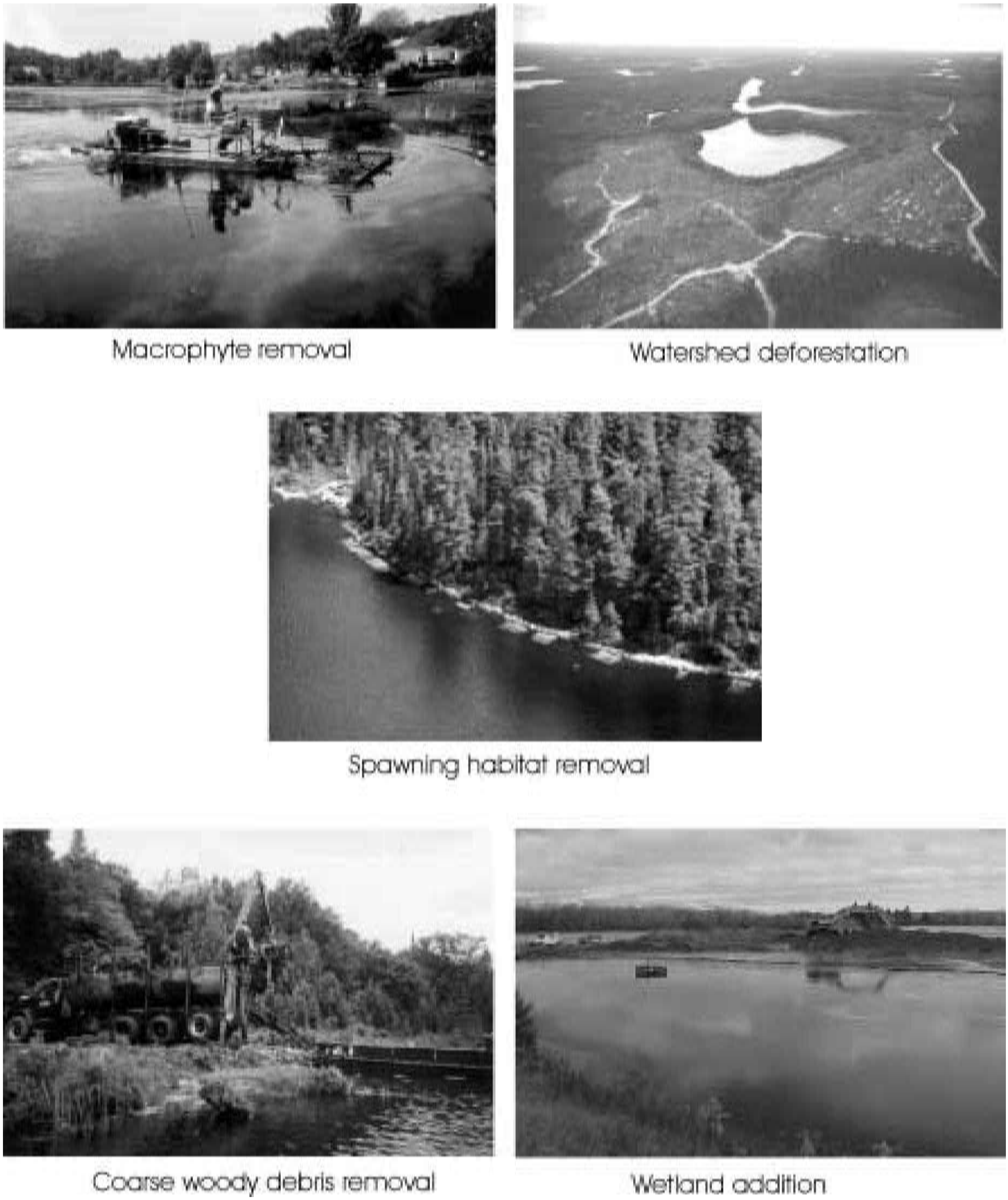

Figure 1 Whole-system habitat manipulation experiments being conducted in Ontario.

Ongoing lake manipulation experiments in the framework

A number of whole-lake habitat manipulation experiments are already underway that fit our hypotheses. The Experimental Lakes Area (ELA) has a long and productive history in whole lake experimentation Schindler, 1991, 1995), particularly for nutrient changes. This tradition has extended to recent habitat manipulation experiments (Fig. 1). The removal of macrophytes from Lake 191 and reduction of lake water volume (drawdown) in Lake 226 (Mills et al., in press) at the ELA fit into our framework (Fig. 1 and Table 1). Manipulation of terrestrial practices in watersheds is another promising approach to understanding aquatic ecosystems. In 1990, the Ontario Ministry of Natural Resources (OMNR) began a long-term, multi-lake experiment to determine the aquatic impacts of catchment and shoreline forestry (Steedman, 2000; Steedman and Kushneriuk, 2000; Steedman et al., in press). The availability of reproductive habitat for lake trout is being manipulated in Whitepine and Helen lakes in central Ontario (McAughey and Gunn, 1995; Gunn et al., 1996; Gunn and Sein, 2000) to simulate the effects of spawning site destruction and directly evaluate the inherent assumptions of DFO's (1986) no net loss policy.

Experimental design

The experimental designs of whole-lake experiments require formidable investments (Schindler 1998). Critics of these experiments suggest that substantial delays may exist before convincing response patterns occur after the manipulation. The alternative to making such an investment is to manage resources in a 'twilight zone' where any policy (or treatment) failure can be blamed on unlucky interactions with environmental factors, and where successes simply reflect good luck with the same factors (Walters et al., 1988). The cumulative cost for ecosystem repair will rapidly outstrip the cost of conducting the good resource management-related experiments at the ecosystem scale.

Alternative designs such as the 'staircase' (Table 2; Walters et al., 1988), the 'Before-After Control-Impact (BACI) (Stewart-Oaten et al., 1986), and their variants are appropriate. Adding more lakes and more years to the monitoring series, before or after, adds to the strength of the results (and increases the need for collaboration). Two years of monitoring before and after each treatment should be a minimum requirement for each lake. The time required for any response to be observed in the adult fish population will, of course, be dependent on life history, with responses observed first in short-lived species or early life stages of longer-lived species. Practitioners may have an intuitive sense of these principles.

We invited 23 biologists, scientists and resource managers attending a workshop in 1998 to rate design options for experimental manipulations of aquatic habitat (Table 3). The manipulations considered by the participants included: a) remove large woody debris from nearshore areas; b) simplify nearshore substrate by adding sand; and c) remove riparian vegetation. By a significant margin, the participants favored a replicated design, with treatment applied over consecutive years (i.e., a staircase or staggered application).

Other design options

Carpenter (1990) points out that the statistical challenges of large scale experiments are less daunting than the practical challenge. Although strongly contrasting treatments are probably more important than replication for lake- or catchment-scale experiments, replication of controversial results can be highly compelling, as at Whitepine Lake (McAughey and Gunn, 1995; Table 1). In our framework for manipulation experiments, it is assumed that interventions such as removal of macrophytes or large woody debris occur once and are not reversed. If manipulations can be reversed, then a 'cross-over' or 'change-over' design develops (Gill, 1978). Options in the 'cross-over' design then include reversing the treatment on each lake after a time (5-6 years depending on life cycle of resident fishes and the results) or beginning/adding a new treatment, for example, exploitation, introduction of a new fish species.

The next steps

The ingredients for success are evident from the important, primarily individual, contributions listed in Table 1. A framework promises even better use of these experiments by providing a mechanism for inclusion of new manipulations. Incentives include 1) consensus on direction, design, and treatments, 2) sharing of data, and 3) access to common reference data.

Table 1 Treatment, lake, hypotheses, data collected, results, an references from whole-system habitat manipulation experiments being conducted in Ontario.

Project	Lake (location[a]) and references	Hypotheses	Manipulation (year started)	Data and Results
Drawdown	Lake 226 (ELA)Mills et al. (in press)	Decrease in lake productivity	Drawdown 1995-1997	Water chemistry, all trophic levels. Loss of lake whitefish recruitment, increased mortality of adults, more than 50% decrease in abundance.
Macrophyte Removal	Minnow Lake (Sud.)	Does a reduction in macrophyte biomass result in a change in fish biomass, production, and community structure?	Harvest macrophytes, 1998 –	Whole lake fish production (all sp.), chemistry, chl a, zooplankton, macrophyte biomass, benthos, periphyton.
	Lake 191 (ELA)	Decrease in northern pike recruitment, abundance, production	Harvest macrophytes 1996-1998	Water chemistry, all trophic levels, pike recruitment, abundance, biomass. More than 50% reduction in northern pike recruitment and total abundance. Increased abundance of other fish species.
Catchment and shoreline disturbance by forestry	Coldwater Lakes Area (TB) Steedman (2000), Steedman and Kushneriuk (2000); Steedman et al. (in press)	1) Does catchment and shoreline clearcutting produce measurable changes in habitat or biota of small, deep, dilute Shield lakes? 2) Do shoreline buffer strips prevent such effects?	Moderate to extensive catchment and shoreline clearcutting on 3 lakes;5 years pre- and 5 years post-isturbance monitoring, 1991–2001	Upland and lake surface climate, stream and lake hydrology, upland geochemistry and hydrology, sedimentation, physical limnology, phytoplankton, periphyton, zooplankton, fish (lake trout, white sucker, littoral species), insect emergence, paleoecology, riparian linkages. Few measurable, and no deleterious aquatic impacts observed after logging treatments.
Habitat Removal	Whitepine Lake, (Sud.)	Will lake trout select alternate habitat when traditional sites are lost? Is lake trout recruitment affected by loss of spawning habitat?	Cover LT spawning substrate, 1992 – 2001	Whole lake, lake trout biomass, age structure, visual counts of fry. Large numbers of alternate sites were selected and no effects on recruitment were detected. The habitat related impact appeared relatively small compared to that of other stresses such as exploitation.
	Helen Lake (Sud.) Gunn and Sein (2000)		Cover LT spawning substrate, 1998 – 2000	

(continued on next page)

Table 1 (continued)

Project	Lake (location[a]) and references	Hypotheses	Manipulation (year started)	Data and Results
Habitat Removal	Upper and Lower Batchawana Lakes (TLW)	Does a reduction in complexity of nearshore habitat result in a change to biomass, production, community structure, or is the effect mainly a redistrubution of fish?	None, reference	Whole-lake fish production estimates (all species, mark recapture), DO, temp, water chemistry, Chl. a, zooplankton, benthos, georeferenced bathymetry, habitat mapping to be put into GIS to test habitat/fish production model, tree mortality plots, underwater camera, fish-food production on wood surface before/ after removal. No detectable limnological effects from wood removal. No clear, consistent association of fishes and their habitat.
	Little Turkey Lake (TLW)		CWD removal, Cover nearshore substrate, 1999	
	Wishart Lake (TLW)		CWD removal, 2000	
	Quinn Lake (SSM)		CWD removal, 1999	
Habitat Additions	Bayside Quarry, Trenton, Ontario.	Does an increase in complexity of nearshore habitat result in a change to biomass, production, community structure, or is the effect mainly a redistrubution of fish?	Add rock rubble reef, 2000	Whole-lake fish production estimates (all species, mark recapture), DO, temp, water chemistry, Chl. a, zooplankton, benthos, georeferenced bathymetry, habitat mapping, underwater camera.
	VanLimbeek Pit, Newmarket Ont.		Increase littoral zone area and create wetland, 2000	
	Stoney Creek Quarry, Stoney Creek, Ontario		Reference	
	Gibb Pit , Stratford, Ontario		Add woody bundles, 2001	

[a] ELA = Experimental Lakes Area; Sud. = Sudbury District; TB = Thunder Bay Region; TLW = Turkey Lakes Watershed, Algoma District; SSM = Sault Ste. Marie, Algoma District.

Table 2 An example of an alternative experimental design – 'staircase', (Walters et al., 1988).

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Lake 1	Monitor	Monitor	Monitor	Monitor	Monitor	Monitor
2	Monitor	Monitor	Treatment	Monitor	Monitor	Monitor
3		Monitor	Monitor	Treatment	Monitor	Monitor
4			Monitor	Monitor	Treatment	Monitor

Table 3 Ranking of design options for the experimental manipulation of aquatic habitat by 23 biologists, scientists and resource managers. Up to 3 treatments (a, b, or c, described in text) were considered for each lake, applied in a synchronized or a staggered manner. Criteria included: 1. Statistical power, 2. Scale of design (# of lakes, # of replicates), 3. Management expectations (i.e. contribution that aids decision making) and 4. Practicality/Logistics.

Design Option	Treatment (4 lakes)	Criteria Ranking	
		Synchronized Implementation	Staggered Implementation
1. Stacked	Reference	1. Low	1. Low
	a	2. Low	2. Medium
	a + b	3. Medium	3. Medium
	a + b + c	4. Low	4. Med.-low
2. One Level	Reference	5. Medium	5. High
	a	6. Medium	6. High
	a	7. Medium	7. Medium
	a	8. Medium	8. Medium
3. Big Bang	Reference	9. Medium	9. High
	a + b + c	10. Medium	10. High
	a + b + c	11. High	11. Med-High
	a + b + c	12. High-Med	12. High
4. Modified Stacked	Reference	13. Medium	13. Medium
	a	14. High	14. Increase Lakes = High
	a	15. Med-High	15. Med-High
	a + b + c	16. Medium	16. Medium

Next steps must address 1) data sharing (we need data standards, a common database, and greater access to data than available from published papers) and 2) obtaining recognition from funding agencies that these collaboratively planned and executed experiments provide greater scientific power, and add more value as data and knowledge. Recognition of the latter strength may provide the greatest incentive for building a collaborative framework and sustaining it. Effective collaboration in large-scale aquatic experimentation has occurred and will continue. A framework such as that proposed here will increase their success and practical impact.

References

Andrewartha, H.G., Birch, L.C., 1954. *The Distribution and Abundance of Animals*. University of Chicago Press, Chicago.

Bassett, C.E., 1994. Use and evaluation of fish habitat structures in the lakes of the eastern United States by the USDA forest service. Bull. Mar. Sci. 55, 1137-1148.

Bradshaw, A.D., 1996. Underlying principles of restoration. Can. J. Fish. Aquat. Sci. 53 (Suppl. 1), 3-9.

Cairns, J., 1991. The status of the theoretical and applied science of restoration ecology. The Environmental Professional 13, 186-194.

Carpenter, S.R., 1990. Large-scale perturbations: opportunities for innovation. Ecology 71(6), 2038-2043.

Carpenter, S.R., Frost, T.M., Heisey, D., Kratz, T.K., 1989. Randomized intervention analysis and the interpretation of whole-ecosystem experiment. Ecology 70, 1142-1152.

DFO (Department of Fisheries and Oceans), 1986. The Department of Fisheries and Oceans policy for the management of fish habitat. Communications Directorate, Fisheries and Oceans, Ottawa, Ontario.

Faith, D.P., Humphrey, C.L., Dostine, P.I., 1991. Statistical power and BACI designs in biological monitoring: comparative evaluation of measures of community dissimilarity based on benthic macroinvertebrate communities in Rockhole Mine Creek, Northern Territory, Australia. Aust. J. Mar. Freshw. Res. 42, 589-602.

Gill, J.A., 1978. *Design and Analysis of Experiments in the Animal and Medical Sciences*. Vols. I and II. Iowa State Univ. Press, Ames, Iowa.

Gunn, J.M., Conlon, M., Kirk, R.J., McAughey, S.C., 1996. Can trained observers accurately identify lake trout spawning sites? Can. J. Fish. Aquat. Sci. 53 (Suppl. 1), 327-331.

Gunn, J.M., Sein, R.S., 2000. Effects of forestry roads on reproductive habitat and exploitation of lake trout (*Salvelinus namaycush*) in three experimental lakes. Can. J. Fish. Aquat. Sci. 57 (Suppl. 2), 97-104.

Imhoff, J.G., Fitzgibbon, J., Annable, K., 1996. A hierarchical evaluation system for characterizing watershed ecosystems for fish habitat. Can. J. Fish. Aquat. Sci. 53 (Suppl. 1), 312-326.

Kelso, J.R.M., Hartig, J.H., 1996. Methods of modifying habitat to benefit the Great Lakes ecosystem. CISTI Occas. Pap.1, 1-294.

Kinsella, W.P., 1982. *Shoeless Joe*. Random House Inc., New York.

Lester, N.P., Dunlop, W.I., Willox., C.C., 1996. Detecting changes in the nearshore fish community. Can. J. Fish. Aquat. Sci. 53 (Suppl. 1), 391-402.

Lewis, C.A., Lester, N.P., Bradshaw, A.D., Fitzgibbon, J.E., Fuller, K., Hakanson, L., Richards, C., 1996. Considerations of scale in habitat conservation and restoration. Can. J. Fish. Aquat. Sci. 53 (Suppl.1), 440-445.

Lincoln-Smith, M.P., 1991. Environmental impact assessment: the roles of predicting and monitoring the extent of impacts. Aust. J. Mar. Freshw. Res. 42, 603-614.

Ludwig, D., Hilborn, R., Walters, C., 1993. Uncertainty, resource exploitation, and conservation: lessons from history. Science 260 (5104), 17, 36.

McAughey, S.C., Gunn, J.M., 1995. Behavioral response of lake trout to a loss of traditional spawning sites. J. Great Lakes Res. 21 (Suppl.1), 375-383.

Mills, K.H., Chalanchuk, S.M., Allan, D.J., Bodaly, R.A., in press. Abundance, survival, condition, and recruitment of lake whitefish (*Coregonus clupeaformis*) in a lake subjected to winter drawdown. Arch. Hydrobiol. Spec. Issues Advance. Limnol.

Peters, R.H., 1980. Useful concepts for predictive ecology. Synthese 43, 257-269.

Rassam, G., 2001. Collaboration beyond our constituency is imperative. Fisheries 26, 24

Reynolds, C.S., 1998. The state of freshwater ecology. Freshw. Biol. 39, 741-753.

Schindler, D.W., 1991. Whole lake experiments in the Experimental Lakes Area. In: H.A. Mooney, E. Medina, D.W. Schindler, E-D. Schulz, B.H. Walker (Eds.), *Ecosystem Experiments and Scope* 45, 122-139. John Wiley and Sons, New York.

Schindler, D.W., 1995. Linking species and communities to ecosystem management. In: C. Jones, J.H. Lawton (Eds.). *Linking Species and Ecosystems*, pp. 313-325, Chapman and Hall, New York.

Schindler, D.W., 1998. Replication vs realism: the need for ecosystem scale experiments. Ecosystems 1, 323-334.

Smokorowski, K.E., Withers, K.J., Kelso, J.R.M., 1998. Does habitat creation contribute to management goals? An evaluation of literature documenting freshwater habitat rehabilitation or enhancement projects. Can. Tech. Rep. Fish. Aquat. Sci. No. 2249.

Steedman, R.J., 2000. Effects of experimental clearcut logging in water quality in three small boreal forest lake trout (*Salvelinus namaycush*) lakes. Can. J. Fish. Aquat. Sci. 57(Suppl. 2), 92-96.

Steedman, R.J., Kushneriuk, R.S., 2000. Effects of experimental clearcut logging on thermal stratification, dissolved oxygen, and lake trout (*Salvelinus namaycush*) habitat volume in three small boreal forest lakes. Can. J. Fish. Aquat. Sci. 57(Suppl. 2), 82-91.

Steedman, R.J., Kushneriuk, R.S., France, R.L., in press. Littoral water temperature response to experimental shoreline logging around small boreal forest lakes. Can. J. Fish. Aquat. Sci.

Stewart-Oaten, A., Murdoch, W.W., Parker, K.R., 1986. Environmental impact assessment: “Pseudoreplication” in time? Ecology 67, 929-940.

Turner, F., 1987. The self-effacing art: restoration as initiation of nature. In: W.R., Jordan, M.E. Gilpin, J.D. Aber (Eds.), *Restoration Ecology*, pp. 47-50. Cambridge Univ., Press, U.K.

Underwood, A.J., 1989. The analysis of stress in natural populations. Biol. J. Linn. Soc. 37, 51-78.

Underwood, A.J., 1993. The mechanics of spatially replicated sampling programmes to detect environmental impacts in a variable world. Aust. J. Ecol. 18, 99-116.

Walters, C.J., Collie, J.S., Webb, T., 1988. Experimental designs for estimating transient responses to management disturbances. Can. J. Fish. Aquat. Sci. 45, 530-538.

Wilson, E.O., 1978. *On Human Nature*. Harvard University Press, Cambridge, Mass.