

SUMMARY OF MAJOR RESEARCH PROJECTS AT THE EXPERIMENTAL LAKES AREA DURING 1997

1 December 1997

1997 has been a year of transition and refocusing for ELA staff and research programs. Funding for two major programs (Long Range Transport of Atmospheric Pollutants, Sustainable Fisheries Initiative) was discontinued as of March. In April, the Department of Fisheries and Oceans (DFO) increased A-Base funding to ELA operations for support of facility operations and baseline monitoring programs. Several long-term staff retired or moved to other locations, completing the final stages of the "downsizing" program. Several graduate student projects came to an end as the students wrote and defended theses. While baseline monitoring and three ecosystem-scale manipulations continued, planning was underway for several additional proposed experimental studies. Construction of new buildings to replace the station manager's residence and the workshop/scuba-laundry facility began in October.

Total site use dropped significantly for the second consecutive year, but approximately 150 research personnel, representing a number of government agencies, universities, and corporations worked on site during the 1997 field season. A two-week field course for aboriginal students was hosted in the fall, and several high school tours and courses were conducted. Construction activity on site is expected to continue into mid-winter. The following is an attempt to summarize the status of major projects by providing some information about their purpose, design and, where possible, major results. It should be noted, however, that data analyses are ongoing and many of the results provided here are preliminary. These projects are grouped under several broad category headings.

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1. BIOMANIPULATION AND SYSTEM PRODUCTIVITY

As humans have perturbed and manipulated aquatic ecosystems for various purposes, unexpected impacts have frequently occurred. Often these impacts have been manifested in major population shifts and alterations of energy flow within the food chain. If we can better understand the factors which control system productivity and structure, and the food chain linkages affected by these perturbations, we will be better able to develop effective management and regulatory strategies for minimizing the adverse effects on aquatic ecosystems of many human perturbations. The following projects are intended to improve our knowledge of these linkages.

1.1 Biomanipulation and Fertilization of Lake 227, and Biomanipulation of Lake 110

Lake 227 was fertilized with phosphorus for the 29th consecutive year in 1997. The original experiment was initiated in 1969 to demonstrate that atmospheric carbon dioxide could provide the carbon necessary for algal blooms in eutrophic lakes. Prior to 1990, all additions included various combinations of nitrogen and phosphorus. The ratio of phosphorus to nitrogen was changed during these previous stages of the experiment to test whether this would influence the dominant algal groups. Since 1990, only phosphorus has been added.

In May of 1993, 40 male northern pike (*Esox lucius*), a piscivorous fish, were added to Lake 227. These fish were transferred from Lakes 222 and 663 at spawning time, when individuals could easily be sexed. An identical transfer of pike to Lake 110 was completed in the spring of 1993. Transfers of pike to Lakes 110 and 227 were undertaken after obtaining approval from the Ontario Ministry of Natural Resources. Major ions, nutrient chemistry, nitrogen fixation, primary production, zooplankton, benthos, and fish populations have been examined in both lakes and in reference Lake 240 throughout the study. Changes in background levels of mercury and organochlorines (PCB's) in fishes and other biota were also monitored during the experiment.

During 1997, phosphorus, as phosphoric acid, was again added to Lake 227 surface waters for twenty consecutive weeks (2.5 litres per week) during the ice-free season. The acid was diluted with lake water in a plastic barrel and dribbled via *Tygon* tubing into the near-shore water. The required acid was carried to the lake weekly. Sodium bicarbonate, to be used as a neutralizing agent in case of an acid spill, is stored on site.

In the fall of 1997, as in 1995 and 1996, Lake 227 was heavily fished to ensure removal of all adult pike. No fish were caught and we assume that all pike have now been removed from the lake. There was no evidence of pike reproduction. This lake will be monitored again in 1998 as a precaution to ensure the success of the pike removal.

Also in the fall of 1997, a single overnight gill net set was placed in Lake 110. Nine adult pike were removed. There is no evidence of pike reproduction in this lake.

1.1.1 The Stoichiometry Projects

During recent years, a joint research undertaking (The Stoichiometry Project), involving DFO and researchers from Arizona State University (Dr. James Elser), the University of Texas at Arlington (Dr. Tom Chryzanowski), and the University of Minnesota (Dr. Robert Sterner), investigated how changes in zooplankton community structure alter the relative availability of N and P supporting phytoplankton and bacterial production. This research centred on changes in the stoichiometry of N and P in two lakes, artificially-eutrophic L227 and oligotrophic L110, following introduction of piscivores (see 1.1, above).

In 1997, the University of Minnesota group continued its research on interactions between food web structure and biogeochemical stoichiometry. The data set on the food web manipulations in lakes 110 and 227 was extended another year, documenting a smaller but substantial population of *Daphnia pulex* in lake 227, and a tremendous bloom of *D. pulex* in lake 110. Amy Galford continued her Ph.D. research on the potential for multiple stable states in zooplankton-phytoplankton interactions, focusing on the effects of varying zooplankton density on phytoplankton density, chemistry, and taxonomy. This study used sets of enclosures in six lakes representing a range of planktonic community structure. Robin Sternberg, an undergraduate assistant, conducted incubation experiments to quantify the overall impact of macrozooplankton on phytoplankton in the same set of lakes. All of these data are currently being analyzed. Amy intends to continue her work next year, with a more explicit consideration of the effects of eutrophication and planktivorous fish populations on zooplankton-phytoplankton interactions.

During 1997, ELA sampling for the Arizona State group was handled by Ms. Galford. In 1998, an ASU team, led by Dr. Elser, will continue sampling in experimental Lake 110 and reference Lake 240. No decision has yet been made on sampling Lake 227. In addition, this team will carry out nutrient (N, P) enrichment experiments in large enclosures placed in Lake 239.

Beginning in 1998, a team from the University of Texas, led by Dr. Chrzanowski and Dr. Jim Grover, will conduct a series of studies focussing on microbial indicators of biological integrity and nutrient stress in aquatic ecosystems. Experiments will be conducted on L227 and L239 as well as two lakes in Texas. They plan a routine sampling of the lakes with nutrient enrichment bioassays prepared in the lab and incubated in bottles suspended in L239. They propose to examine several chemical and biological variables that may provide not only a broadly applicable approach to understanding the biological consequences of nutrient loading in aquatic systems, but also a means of predicting the resulting community structure. The indicators they will examine are seston C:N:P ratio, species level responses of algae to nutrient bioassays, community level responses of bacteria to nutrient bioassays community structure of algae, community structure of bacteria, and the estimate ratio of algal to bacterial specific growth rates.

1.2 Biomanipulation of Lake 221

Lake 221 is the site of a biomanipulation experiment that started in 1987 when 123 northern pike were transferred to this lake from nearby Lake 222. Water chemistry, primary productivity, phytoplankton populations, zooplankton, zoobenthos, and fish populations were studied in Lake 221 before and after pike addition. The Recovery phase of the experiment started in 1994 when approximately 80% of the northern pike were removed from this lake. Netting continued in 1995 and 1996. In the fall of 1997, 19 pike and some yellow perch (*Perca flavescens*) were netted and removed from the lake. The presence of several younger fish in this catch indicates that the pike are now reproducing in this lake. Water chemistry, phytoplankton, and zooplankton populations were monitored monthly in 1997.

1.3 Experimental Cropping of Lakes

The lake whitefish populations of Lakes 258, and 305 were experimentally fished to simulate a pulse commercial fishery in 1981 and 1982. Recovery of these populations has been monitored by over-night sets of gill nets one to two nights per year since the initial cropping. Reference lakes 259 and 468 are also monitored by similar netting. In 1997, only Lake 305 was fished. Data from reference lakes are used to interpret lake whitefish data from other ELA experiments.

1.4 Northern Pike Project - Macrophyte Removal

Lake 191 at the Experimental Lakes Area is the site of a macrophyte removal experiment to evaluate the impact of littoral zone alteration on recruitment, growth, and change in productivity of a northern pike population. The effects of this removal on resident fish populations, especially northern pike, are evaluated using mark-recapture studies. Changes in water chemistry and all trophic levels in the lake are monitored during the study. Macrophyte populations are censused in August of each year for species composition, biomass, and area coverage.

After two years (1994, 1995) of background study, macrophyte harvesting began in 1996. A mechanical harvester removed fifty percent of the macrophytes present in the lake by August 1996. Removal at the same level continued in 1997.

The primary changes that occurred during 1996 and 1997 involved fish populations. The population structure and abundance of northern pike changed almost immediately after harvesting began. Total abundance has decreased and abundance of age 0 (young of the year) northern pike has decreased. Few

age 0 pike were present in the cut areas. Larger, intermediate-sized northern pike were displaced from littoral areas to deeper water. Abundance of prey species (yellow perch and pumpkinseed (*Lepomis gibbosus*)) increased.

This study will continue in 1998; macrophytes will be harvested for the third year and impacts documented on the water chemistry and biota of the lake.

Nearby Lake 165 continues to be monitored as a reference lake for this experiment.

2. PHYSICAL PERTURBATIONS

This section includes experimental studies in which some physical aspect of the lake ecosystem has been manipulated. In most cases, this has involved experimental alteration of the water level, as a simulation of what typically occurs during the creation and operation of reservoirs.

2.1 Experimental Lakes Area Reservoir Project (ELARP)

In June 1993, following 2 years of background study, ELA Lake 979, a small wetland system, was flooded to a depth of more than a metre. Mobilization of methyl mercury within the flooded ecosystem and release to the atmosphere of CO₂ and CH₄ in response to the flooding were monitored intensively. A non-flooded wetland system (ELA Lake 632), was monitored as a reference. Following winter drawdown, flooding of Wetland 979 was repeated in summer and fall of 1994 and 1995, as detailed studies continued in both wetland systems. In all three years, dramatic increases in methyl mercury and in release of the greenhouse gases were observed in response to flooding.

With the first phase (5 years) of the experiment completed, 1996 was devoted primarily to data analyses and scientific paper writing. Although flooding was repeated and some monitoring continued. A major paper by Kelly et al. (see below), published in 1997, summarized the results from the first phase.

During 1997, the 979 wetland was flooded for the fifth consecutive summer. Greenhouse gas (GHG) emissions and methyl mercury mass balance budgets were monitored. GHG and methyl mercury concentrations in the 979 reservoir remained elevated. GHG concentrations have decreased only slightly over the five years. Methyl mercury mass-balance budgets indicate that mercury methylation rates have begun to slow, but remain above pre-flooding levels. Tree swallow reproductive success and methyl mercury bioaccumulation in nestlings near the reservoir was continued in 1997, but no results are yet available.

The drop-off in methyl mercury concentrations while GHG emissions remain relatively constant is of interest. At the outset of this study, the research team hypothesized that GHG fluxes and methyl mercury concentrations would be linked over time. Most of the flooded vegetation has now decomposed, which means that current gas fluxes are being supported more by peat decomposition. The researchers now believe that methylation must be linked more to decomposition of vegetation (which had slowed considerably 4 years after initial flooding), but not linked as strongly to peat decomposition. This has important implications for interpreting gas fluxes in older reservoirs, which often remain high after many decades, while mercury in fish decreases after 1 to 2 decades. The ELARP research team is recommending that fish be removed prior to and just after reservoir flooding, so that the top of the food chain is not exposed during the periods of highest methylating activity.

Kelly, C.A., J.W.M. Rudd, R.A. Bodaly, N.P. Roulet, V.L. St. Louis, A. Heyes, T.R. Moore, S. Schiff, R. Aravena, K.J. Scott, B. Dyck, R. Harris, B. Warner, and G. Edwards. 1997. Increases in fluxes of greenhouse gases and methyl mercury following flooding of an experimental reservoir. *Environ. Sci. Technol.* **31**: 1334-1344.

2.1.1 "Bioreporter" Project

In a related project, the use of a genetically engineered "bioreporter" to measure the bioavailability of inorganic mercury in lake water is being tested. Inorganic mercury is turned into methyl mercury, which is more toxic, by bacteria that carry out methylation. The inorganic mercury must enter the bacterial cells to become methylated, but a lot of mercury in aquatic systems is bound to particles and DOC, and so is not bioavailable for methylation. The bioreporter system, which is a strain of bacteria that produces light when mercury enters its cells, allows us to quantify bioavailability. The ELA part of this work has been done by Karen Scott, who is a graduate student in Microbiology at the University of Manitoba. She did the first measurements of bioavailability in freshwater, pristine lakes this summer, and will continue her project next summer, looking at precipitation, streamwater, and different kinds of lake water.

2.1.2 Hydrology and Methylmercury Biogeochemistry of Headwater Catchment 632

1997 was the final year of a five-year study of the hydrology and methylmercury biogeochemistry of the 632 headwater catchment. Ph.D. student, Brian Branfireun, and Dr. Nigel Roulet of McGill University conducted it. This study involved the measurement of groundwater and surface water fluxes, continuous measurement of soil moisture and transient water table development using Time Domain Reflectometry (TDR), and methylmercury concentrations and fluxes in water and sediments. The study objectives are to delineate zones of mercury methylation; determine the biogeochemical controls on mercury methylation, and; examine the catchment-scale fluxes of methylmercury with the intent to determine, at the process level, why catchments containing wetlands export more methylmercury than their strictly upland counterparts. No future work on this project is currently planned.

Branfireun, B. A., A. Heyes, and N. T. Roulet. 1996. The hydrology and methylmercury dynamics of a Precambrian Shield peatland. *Water Resources Research* **32(6)**, 1785-1974.

Branfireun, B. A., D. Hilbert, and N. T. Roulet. 1997. Sinks and sources of methylmercury in a boreal catchment. *Biogeochemistry* (in press).

Branfireun, B. A., and N. T. Roulet. 1997. The baseflow and stormflow hydrology of a Precambrian Shield headwater peatland. *Hydrological Processes* (in press).

Devito, K. J., M. J. Waddington and B. A. Branfireun, 1997, Flow reversals in peatlands influenced by local groundwater systems. *Hydrological Processes* **11**:103-110.

2.1.3 Decomposition Rates Study

A research team from McGill University, led by Dr. Tim Moore, also carried out mercury cycling studies on the 632 reference wetland. In 1997, they retrieved the last set of litter bags from two sites in the 632 wetland catchment. This was part of the ELARP study, in which the McGill team examined the effect of

shallow impoundment on the decomposition rates of different tissues. The last samples from 979 were retrieved in 1996, and 632 was the "control" system. No results have yet been published.

2.2 Lake 226 Drawdown Study

The purpose of the Lake 226 Drawdown experiment is to study the impacts of winter water level drawdown, simulating the water level fluctuations in a hydroelectric reservoir. The lake has been studied for one year prior to drawdown (1994) and for three years after drawdown (1995, 1996, and 1997). In the winter of 1994-95 the water level was reduced by 2 m below natural levels. This drawdown was achieved by blasting the natural outlet channel. Precautions were taken to avoid fish mortalities during blasting by using reduced charge sizes, and by removal of all large fish from the bay adjacent to the outlet combined with the installation of a fish barrier at the head of the bay. No fish mortalities were observed. Approximately 30% of the lake volume was removed, resulting in a decrease of about 11% in lake surface area. The lake rose during the spring and early summer by about .5 m, but the level stayed relatively constant during the summer and fall at about 1.5 m below natural levels, as runoff into the lake was approximately balanced by evaporation. In the winters of 1995-96 and 1996-97 the water level was reduced by 3 m below natural levels. This drawdown was achieved by siphoning water through four 4" plastic pipes. The lake rose during the spring and summer periods of 1996 and 1997 due to snow melt and summer rains. Lake elevation at freeze-up in 1996 and 1997 was approximately 0.8 m below natural levels.

Preliminary indications are that the following impacts occurred in the lake as a result of water level drawdown. Approximately 10% of surface area of the lake has been dry in the summer and the productivity of this portion of the lake was lost to fish populations; although in 1995, a warm summer resulted in the total number of emerging insects from the lake being only slightly reduced after drawdown. Standing stocks of benthic macroinvertebrates decreased in the shallow littoral zone of the lake. There has been reproductive failure of lake whitefish in the lake in all years of drawdown, probably due to the exposure of incubating eggs after spawning. The total number of lake whitefish in the lake has declined since drawdown began. Acoustically tagged fish were followed during the 1995 and 1996 fall spawning seasons, and time of spawning, spawning sites and substrate used for spawning have been identified. Eggs were located at one of these sites in the fall of 1997 by a cooperative SCUBA diving sampling effort of DFO and OMNR. Analysis of stable isotopes of carbon and nitrogen indicated that lake whitefish were feeding mainly on food from the pelagic food chain, perhaps mostly Chaoborus. Submerged vegetation declined dramatically after drawdown although terrestrial vegetation began to invade the exposed shores. Littoral algal production decreased due to loss of habitat and to an increased sedimentary character of the communities. Spatial variability increased. Increased resuspension of fine sediments was less noticeable than expected; however, increases in the ratio of the volume of the epilimnion to the volume of the hypolimnion have apparently resulted in decreased summer hypolimnetic oxygen concentrations. Phytoplankton species composition was unaffected, although total biomass increased due to increased abundances of chrysophytes and dinoflagellates. Bacteria also appear to have increased.

The lake will not be drawn down over the winter of 1997-98; rather, the water level will be allowed to come back to natural levels over the spring and summer of 1998. This will more closely mimic the water levels in actual hydroelectric reservoirs and will test the effect of water level on fish reproduction, habitat, and productivity. Monitoring of the lake in the 1998 summer field season will depend on funds available.

2.3 Upland Flooding Experiment (proposed)

A new reservoir experiment is proposed for the Experimental Lakes Area. The purpose of the Upland Flooding experiment is to study the greenhouse gas and mercury impacts of flooding forested upland areas. It would be, therefore, a follow-up to the ELARP study (see 2.1, above).

During the summer and fall of 1997, considerable areal and ground reconnaissance was carried out to select candidate sites for this experiment. This was followed by detailed mapping and ground truthing of the selected sites. Four areas near the junction of the Teggau Trail and the Pine Road (adjacent to and in the watershed of Roddy Lake (468)) are proposed for flooding. The study schedule proposed is for a year of pre-flooding observations in 1998, for flooding to occur in the spring of 1999, and for post-flooding observations in 1999, 2000, and 2001. The four flooded areas proposed are: a wetland (Site 1), a moist forest (Site 2), a dry forest (Site 3), and a very dry forest with areas of exposed bedrock (Site 4). The approximate sizes of each of these proposed impoundments are as follows:

Site	Area (ha)	Mean depth (m)	Volume (10 ⁴ m ³)	Dike length (m)
Site 1	3.7	0.5	1.85	80
Site 2	0.61	1.0	0.61	190
Site 3	0.70	1.2	0.84	130
Site 4	0.71	1.0	0.71	350

Reservoirs would be filled by pumping water from Roddy Lake. Water from Sites 1 and 2 would drain back to Roddy Lake, whereas Sites 3 and 4 would drain to Lake 239. The pump would be electric or diesel-powered. If diesel is chosen, double walled fuel storage tanks would be used, with fail-safe systems to detect leaks. Tank(s) would be located approximately 175 m from the shore of Roddy Lake.

Water renewal times of approximately 2 weeks during the open water season are anticipated. The dike construction method is yet to be determined. Dikes may be gravel or gravel and wood construction. Maximum dike height would be approximately 2 m. Approval of the project configuration and dike construction methods from the Regional Engineer (Ontario Ministry of Natural Resources, Thunder Bay) would be sought if this is determined to be required by the ELA Management Board.

No chemical or physical substances would be introduced into Roddy Lake or any of the impoundments. Rather, naturally occurring substances only would be monitored as part of the experiment. We anticipate that levels of carbon dioxide and methane, derived from decomposition of vegetation and soil carbon will increase in the impoundments. We also anticipate that levels of methyl mercury in the water and biota of the impoundments would increase as result of impoundment.

One or two species of fishes would be transferred to the impoundments. These would probably be yellow perch and finescale dace. Both are naturally occurring in the area and both occur in both Roddy Lake and Lake 239.

3. NATURAL VARIABILITY AND CLIMATIC FACTORS

In order to objectively assess the effects of anthropogenic perturbations on aquatic ecosystems, it is essential to systematically monitor non-perturbed systems over long time periods. Only thus can we hope to evaluate the effects of naturally-occurring events (weather, cyclic climatic oscillations) on these ecosystems and factor these effects into our interpretations of impacts resulting from human activities. Of course, natural perturbations also can have significant effects on processes within these small lake ecosystems.

3.1 Impact of Disturbances on the Lake 239 Watershed

Long-term hydrological, Meteorological, and chemical monitoring in the calibrated catchments of this watershed continued during 1997. Portions of the watershed were perturbed by a major forest blow-down in 1973, and by forest wildfires in 1974 and 1980. This and other ELA watersheds have been subjected to extremes of precipitation over the monitoring period. The monitoring is intended to evaluate long-term effects of these and other natural perturbations on the lake ecosystems, and to calibrate other hydrological studies at the ELA. The watershed has been continuously monitored for 29 years. No chemical additions are made.

Among the scientific results in 1997 from this long-term study was a paper published in *Biogeochemistry* by Schindler *et al.* (see section 3.2, below) describing climate-induced changes in dissolved organic carbon budgets in this watershed. A manuscript (now under review) by Shearer *et al.* describing how meteorological factors drive in-lake processes, particularly primary production, is intended for publication in a special "lake districts" issue of *Freshwater Biology*.

3.2 Direct and Indirect Effects of Ultraviolet Radiation

Over the past several years, a research group from the University of Alberta, led by Dr. David Schindler, has carried out a variety of studies focusing on the effects on lakes and streams of ultraviolet-B (UV-B) radiation. These studies have examined the role of dissolved organic carbon (DOC) as a shield against UV-B in freshwater systems.

During 1997, the Alberta work at the ELA was carried out by Bill Donahue, a Ph.D. student under the supervision of Dr. Schindler. Mr. Donahue continued and completed his field studies in support of his thesis, and is now preparing to defend this thesis. He investigated, using enclosure experiments, the interactions of UV radiation in the epilimnion of lakes. He also conducted a survey of more than 60 ELA lakes and streams to assess the range of natural interactions of UV with DOC. A second part of his thesis research involved experimental studies, using artificial stream channels, of UV effects on stream biota. In addition, Mr. Donahue collaborated with Dr. Michael Turner, Dr. Peter Leavitt, and Dr. Kate Duff to investigate the role of UV in structuring epilithic communities. Final results should be available soon in Mr. Donahue's thesis and in published papers.

Dr. Schindler has been seeking funding and collaborators for two proposed whole-ecosystem experimental studies using ELA lakes. One would examine the role of allochthonous DOC in lakes by experimentally reducing the DOC entering a lake, either through stream diversion or by digestion of the incoming DOC. The second study would experimentally deepen the mixed layer and thermocline of a lake and examine the effects of a diminished hypolimnetic volume. Both of these experiments would mimic effects observed in ELA lakes during a two-decade period of climatic warming, and would provide a preview of what might be expected in many boreal lakes in response to global warming. A third experiment, involving addition of CO₂ to a lake, has also been proposed.

The ELA work on UV and DOC interactions spurred a 1994 symposium in Jasper, Alberta, hosted by Dr. Schindler. This symposium resulted in a special January 1997 issue of the journal *Biogeochemistry*, which focused on "dissolved organic carbon as an integration of global stresses on freshwater". The following papers describing ELA research results were part of this issue:

Schindler, D.W., and P.J. Curtis. 1997. The role of DOC in protecting freshwaters subjected to climatic warming and acidification from UV exposure. *Biogeochemistry* **36**: 1-8.

Schindler, D.W., P.J. Curtis, S.E. Bayley, B.R. Parker, K.G. Beaty, and M.P. Stainton. 1997. Climate-induced changes in the dissolved carbon budgets of Boreal Lakes. *Biogeochemistry* **36**: 9-28.

Curtis, P.J., and D.W. Schindler. 1997. Hydrologic control of dissolved organic matter in low-order Precambrian Shield lakes. *Biogeochemistry* **36**: 125-138.

3.3 Metalimnetic and Hypolimnetic Chlorophyll Peaks

For the second consecutive summer, Dr. F.J. DeNoyelles, Jr. and Dr. David Graham of the University of Kansas conducted a late summer survey of several ELA lakes to evaluate the magnitude and status of metalimnetic and hypolimnetic chlorophyll maxima attributable to concentrations of algae and photosynthetic bacteria at distinct depth strata. If they succeed in obtaining additional U.S. funding support, they plan to return to the ELA in 1998 to expand this study.

This work is a follow up to extensive studies of these peaks conducted at the ELA by Dr. DeNoyelles and other researchers during the 1970's and 1980's. Results from lakes at the ELA will be compared to those from artificial lakes in Kansas and other sites much further south. Similar work is being conducted for the Coldwater Lakes study area near Atikokan, Ontario.

4. ACIDIFICATION AND RECOVERY

Acidification of aquatic ecosystems by anthropogenically-derived acidic precipitation has been widely recognized for almost two decades as a widespread environmental problem in many parts of eastern Canada, the northeastern United States, Scandinavia, and elsewhere. While certain legislative and regulatory measures have already been adopted to alleviate this problem, considerable uncertainty remains about the ultimate effectiveness of these measures and about the ability of natural ecosystems to spontaneously recover from significant acidification once acidic input has been reduced. The Long Range Transport of Acidic Pollutants program, under which ELA acidification studies have been funded, has now been terminated. However, the ELA has an obligation to continue monitoring experimentally acidified ecosystems until such time as they have clearly returned to a healthy, natural state. In doing so, we may also be able to provide legislators and managers with answers to remaining questions about the effectiveness of current control measures and the probable nature of ecosystem recovery from acidification.

4.1 Recovery of Lake 223 from Acidification

Lake 223 was acidified with sulfuric acid from 1976 (pH 6.7) to 1983 (pH 5.1), and was then allowed to gradually recovery from 1984 (pH 5.4) to the present time. The purpose of the acidification phase of the experiment was to document chemical and biological changes of progressive acidification, concentrating on the changes that occur during the initial stages of lake acidification. The purpose of the recovery phase of the experiment was to document the rate and extent of chemical and biological recovery. The acidification phase of the experiment was intentionally terminated before most fish species were extirpated from the lake, but at a stage where their elimination was assured had acidification continued.

Pre-acidification pH (6.5 – 6.7) was achieved in 1995 and 1997 is third year of study after complete pH recovery. Biological recovery has lagged chemical recovery in Lake 223, especially for fish populations. Lake trout (*Salvelinus namaycush*) abundance is still gradually increasing, but total abundance remains less than that prior to acidification. White sucker abundance has now decreased to that prior to acidification; growth and condition (fatness) have now increased to pre-acidification values. The fathead minnow (*Pimephales promelus*) population has now returned to former abundance values. Zooplankton community structure is now very similar to that prior to acidification.

Study of Lake 223 will continue in 1998, but at a very reduced work schedule. Biological recovery has occurred in Lake 223, with the exception of the continued absence of a few major species such as *Mysis relicta* and slimy sculpin (*Cottus cognatus*).

4.2 Recovery of Lake 302S from Acidification

Background

The Lake 302S whole-lake experiment is important to understanding the ability of aquatic ecosystems to recover naturally (i.e., without human intervention) from anthropogenic impacts (i.e., acidification). This productive experiment has contributed ca. 60 primary publications (published [49], in press [1], under review [4], or in preparation [4]), 6 graduate theses and about 25 ancillary publications since 1985.

1997 was the lake's sixth year of recovery from acidification to pH 4.5. The target pH has remained at 5.8 since 1994, compared to 5.1 in 1992 and 1993. Complete ecosystem analysis continued as in past years, including: hydrology, water chemistry (plus metals), and many components of the pelagic and littoral food webs, albeit at lower sampling effort because of funding limitations.

General Conclusions About Recovery

The good news is that the simple reduction of acid inputs, by itself, can result in some ecosystem recovery. Unfortunately simple reduction of acid inputs has been insufficient to (initially) restore the chemical and biological composition and functioning of the ecosystem at this intermediate pH (5.8). As a result, the lake is recovering to a state that differs from its pre-acidification state; neither geochemical nor biological recovery are proceeding along their acidification trajectories so that there is hysteresis in the recovery process. Reducing the lake's pH below 5 may also have impaired the lake's biogeochemical ability to buffer itself against acid inputs. With the impairment of chemical recovery, the stage is only partially prepared for biological recovery, which has been impaired. For example, biological diversity remains lower. As a result, biological structure and function often remain different than that seen during the acidification trajectory, i.e., prior to the major changes caused by acidification. In some cases, the chemical milieu of the lake has also been less favourable during recovery than it was before. In addition,

complex interactions between biological and chemical properties will make prediction of recovery of ecosystem properties difficult.

Geochemical recovery has been both incomplete and prolonged. Recovery was often incomplete until certain threshold values were achieved (e.g., nitrogen and the nitrification process), or was prolonged (e.g., carbon – dissolved organic carbon production), or previously unobserved features were seen (e.g., iron [unexpected increases] and internal alkalinity generation [unexpected suppression]).

The lake's arguably most important biogeochemical property, its ability to generate alkalinity internally, remains impaired. Internal re-acidification has been regularly observed, as a result, the efficiency of acidifying substances is greater during the recovery period than it was during acidification. This may have been related to chemical changes that are mediated biologically, e.g., sulfate reduction and nitrification, and were possibly diminished by insufficient supplies of reduced carbon. Concentrations of most metals remain elevated during the recovery period; temporary increases in iron may be linked to periods of internal re-acidification via re-oxidation of previously reduced sulfate.

Although some uneven biological recovery has been occurring, albeit in the absence of fish other than pearl dace (*Semotilus margarita*) (and fathead minnows recently), symptoms of a biocoenotic disturbance remain. Biotic composition and function remain highly variable, with littoral and pelagic recoveries differing compositionally and functionally. Recovery of biological diversity has been uneven: diversity is recovering in phytoplankton, but not in zooplankton or fish (constrained in part by the absence of natural invading populations).

Phytoplankton biomass, which had earlier achieved all-time maxima due to dinoflagellate blooms, has been returning to pre-acidification levels. In contrast, epilithic algal biomass remained low until 1997; annual blooms of littoral filamentous green algae have been variable in occurrence and generally low in abundance. Phytoplankton productivity remained unaffected by the change in pH in contrast to epilithic productivity, which remained disrupted until 1997. Algal nutrition shifted: planktonic phosphorus deficiency continued; while nitrogen deficiency increased back to its pre-acidification state due to decreasing ammonia levels; carbon limitation of benthic algae, which was aggravated by acidification, persisted although less so in 1997. The macrophyte community has not appeared different during recovery from those in nearby reference lakes. Annual zooplankton abundance and biomass have been fluctuating considerably, consistent with a further decline in zooplankton diversity. Chironomid emergence has slowly been declining to its pre-acidification levels. In contrast, Cladocera continued to flourish in the near shore region until 1997, possibly due to the absence of fish predation. Until 1996, only a population of pearl dace survived the acidification period, and it regained its reproductive ability at this intermediate pH.

Preliminary Observations in 1997

Although we remain in the early stages of data analysis, 1997 was a year full of surprises. The decision to continue this experiment holding the target at pH 5.8, albeit with a reduced sampling effort, was a wise one.

Biological surprises were common, as populations invaded previously empty niches, with attendant trophic consequences. For example, minnow populations (specifically fathead minnows and to a lesser extent, the pearl dace) have exploded into the near shore region. Following this fish increase, the previously persistent inshore blooms of Cladocera are now gone. As well, there was a blossoming of sponges that may have resulted from the loss of an insect grazer (Trichoptera) that have now been eaten by the minnows.

Epilithic productivity finally appears to be in the early stages of restoration. This metabolic recovery has been associated with recovery in the algal assemblage of species, and an increase in dissolved inorganic carbon as pH values increased nearer to 5.8. There was also a sudden resurgence of metaphytic filamentous green algae, although in much reduced quantities compared to pH 4.5.

Despite the reduced abundance of Dinoflagellates, the (bacterial related) biotoxicity associated with the blooms was still inducible with addition of organic carbon compounds and iron. This could mean that toxicity to recovering biota may occur in special circumstances, as happened during acidification.

For as yet unknown reasons swallows continue to be unsuccessful in their nesting attempts. Preliminary work suggests that calcium insufficiency and metal toxicity in food do not appear to be causes.

The geochemical story especially remains incomplete until further analysis, but based on our need to increase acid additions to maintain the target pH 5.8, the previously suppressed internal generation of alkalinity may finally be showing some signs of recovery.

Plans for 1998

If we are successful in obtaining support for this experiment, then we will probably maintain the target pH at 5.8 to assess whether recovery can proceed beyond that already seen. This will allow us to further determine whether human intervention is needed to restore the ecosystem near to its original state. We would continue many of the ecosystem measurements as in previous years, except where downsizing has compromised our abilities.

Our additional plans, pending funding, include: determining whether the availability of reduced carbon is controlling the rate of recovery of internal alkalinity generation; analysis of the interaction of recovery from acidification with global change (specifically the interaction with increased UV_b and CO₂; see paper by Schindler et al, 1996, Nature 379:705-708); examination of the effects on biological populations of long-term stress; further analysis of the potential for dinoflagellate blooms to be toxic to biological populations during acidification and recovery; and developing strategies for food web reconstruction.

Additional Challenges

As has been the case in previous years, recovery from acidification should remain a priority of the Government of Canada (e.g., DOE), and yet is poorly understood (see paucity of recovery papers in Water, Air, and Soil Pollution Vol. 85, 1995). Recovery will also be an important issue in eastern North America for several decades (see time trend analysis papers in same volume) as well as in the remainder of the planet as acidification in Asia and the southern hemisphere accelerates.

Our future ability to continue this experiment remains tenuous because DFO formally withdrew its support of LRTAP initiatives beyond the 1996/97 fiscal year. It is unclear whether the ELA will be able to obtain sufficient financial support to maintain the necessary experimental additions, let alone continue the ecosystem recovery studies or to initiate new research. In 1997/98 we were able to continue the limited acid additions required, and continue biological and chemical sampling although at a reduced level.

4.3 Recovery of Lake 302N from Acidification

Lake 302N is the northern basin of Lake 302, separated from the south basin (described in 3.3, above) since 1981 by vinyl curtains. Experimental loading of NaNO_3 , Na_2SO_4 and HCl were made during 1992 and 1993, along with additions of H_3PO_4 at a rate of 1:10 P:N, as part of a study to define the role of phosphorus supply in the lake's internal generation of alkalinity. The water pH was maintained at 5.4 during those years.

The experiment served to demonstrate that phosphorus additions can stimulate internal alkalinity generation, thereby serving as a potentially cost-effective remediation strategy. Concern for increased risk to the fish populations dictated that experimental additions be stopped and that the recovery of the lake be monitored.

In 1994 through 1996, a limited amount of concentrated HCl was added to prevent the pH from rising above the target value of 5.8. Monitoring of various limnological parameters continued.

During 1997, no acid was added to this lake basin. The pH was permitted to rise to natural levels. Monthly monitoring of in-lake parameters continued. The populations of lake whitefish and other organisms in this basin serve as potential seed populations for the restocking of Lake 302 South.

5. PERSISTENT TOXIC SUBSTANCES

Certain substances, when released into natural ecosystems, may persist for years in a toxic form, and may bioaccumulate within the food chain to create health problems for higher organisms, including humans, particularly when exposures are chronic. While such persistent toxicants are often experimentally studied under laboratory conditions, only studies conducted in real ecosystems can effectively examine the complexity of ecosystemic pathways and compartments in which these substances move and accumulate. We require some controlled experimentation in real ecosystems to validate existing and proposed regulatory standards for these substances.

In addition, these experimental studies with persistent toxicants provide an opportunity to determine the physiological bases of ecosystem effects, thereby identifying indicators of stress at lower (physiological, histological) levels of biological organization. Once identified, these indicators can be extremely useful for the assessment and remediation of environmental problems.

5.1 Organochlorines and Poly-Aromatic Hydrocarbon Study

The purpose of this study was to evaluate the effects of chlordane, toxaphene, and a dibenzofuran on lake trout and white sucker populations in Lake 260. It formed the basis for a Ph.D. thesis completed by Peter Delorme (University of Manitoba) in 1994.

In 1988 and 1989, low concentrations of each compound were injected into the bodies of adult lake trout and white sucker. These individuals were recaptured over a series of years to evaluate changes in spawning efficacy, through egg incubation experiments, and changes in the annual survival of the injected individuals. Non-injected individuals were monitored each year as reference fish for the injected fish. Most of the injected individuals have been removed from the population for analysis of residue in their tissues.

The lake trout population in Lake 260 is still monitored each year to determine how many of the injected individuals remain in the population. Only two injected individuals were captured in 1997; both had been injected with the "control" substance (corn oil), originally used to evaluate the effects of injecting the solution without the toxicant in 1988. No individuals that had been injected with chlordane, toxaphene, or dibenzofuran were recaptured in 1996 or in 1997..

5.2 Cadmium Addition to Lake 382

Between 1987 and 1992, trace amounts of cadmium were experimentally added to the surface waters of Lake 382. The purpose was to test the adequacy of existing guidelines for protecting against chronic cadmium contamination effects in real aquatic ecosystems. Levels of cadmium in Lake 382 were gradually raised each ice-free season so that approximately 200 nannograms per litre ($\text{ng}\cdot\text{L}^{-1}$) were present during the summers of 1991 and 1992. This is still almost 2 orders of magnitude below the Canadian drinking water standard, but at a level where biological impacts would probably occur if the treatment were chronically maintained. By the end of 1992, a total of 7 kg of cadmium had been added to Lake 382. Most of this has now moved into the lake sediments. No cadmium has been added since 1992, but monitoring continued through 1996 to observe responses to the "zero discharge strategy".

In 1997, no funding was available to continue the detailed monitoring. Dr. Diane Malley, the study coordinator, has now retired from DFO. Basic chemical parameters and phytoplankton populations were monitored monthly in 1997. No fish sampling was done this year. The current plan calls for cadmium monitoring to be done every second year, with 1998 being the next year of the cadmium sampling cycle.

5.3 Effect of Metal Mixtures on Bioavailability and Bioaccumulation of Cadmium

Molluscs were evaluated as biomonitoring tools for the Canadian mining industry. Bivalve molluscs were found to be appropriate biomonitors of metals in the aquatic environment, particularly for characterizing spatial and temporal trends in metal contamination. Further research was recommended to develop molluscs as biomonitors of tissue-residue based effects of metals.

The effects of a metal mixture (Cu, Zn, Pb and Ni) on Cd bioavailability and accumulation by a freshwater unionid mussel, *Pyganodon grandis*, and the isoetid macrophyte, *Eriocaulon septangulare*, were examined *in situ* at the Experimental Lakes Area, Ontario, Canada. A limnocorral experiment was conducted during the summer of 1992, in which Cd was added alone to the water column in treatment 1 and with the metal mixture in treatments 2, 3 and 4 to raise background sediment Cd concentrations by 7 times. Copper, Zn, Pb and Ni were added to treatments 2, 3 and 4 to raise sediment concentrations by 3, 4 and 7 times, respectively. Treatments with the metal mixture had longer residence times for Cd in the water column than the treatment with Cd alone. Cadmium accumulation in mussels was significantly reduced in treatments with the highest concentration of the metal mixture compared to treatments with the lowest concentration of the metal mixture or with Cd alone. Tissue metallothionein levels were highest in the kidney and tended to decrease in treatments with increasing metal addition. The effect of competition on the partitioning of Cd in the water column appeared to be a less important phenomenon than competition at binding sites on the mussels in determining Cd uptake by the mussels.

In the summer of 1995, littoral sediments were spiked with Cd alone and with the metal mixture at three increasing concentration levels (2, 4 and 6 times background). *Eriocaulon septangulare* were planted in the spiked sediment and placed at 0.5 m water depth in the littoral zone. The distribution of Cd among

sediment fractions (easily-reducible, reducible and organic), in porewater, and in macrophytes was determined every second week for 10 weeks. The metal mixture had a significant affect on the distribution of Cd among geochemical fractions in the sediments after 2 and 8 weeks, but not after 10 weeks. At the highest concentration of the metal mixture, Cd shifted from the easily-reducible (Mn-oxide) fraction, which is considered more “bioavailable”, to the less bioavailable, reducible (Fe-oxide) and organic fractions. The highest Cd concentrations were found in the shoots of plants in the treatment with Cd alone and the treatment with the highest concentration of the metal mixture.

This work has formed the basis for a Ph.D. thesis by Robin Stewart, at the University of Manitoba, which was completed in 1997. In addition, one paper based on the mussel study is now under review for publication in the *Canadian Journal of Fisheries and Aquatic Science*. A second manuscript, coauthored by Dr. Diane Malley and based on the macrophyte study, will be submitted to *Environmental Toxicology and Chemistry* for possible publication.

6. STUDIES IN, AND LINKAGES WITH, TERRESTRIAL CATCHMENTS

6.1 Nitrogen Cycling in Upland Precambrian Shield Catchments

The elevated deposition of nitrogen (N) compounds is an increasingly recognized source of acid rain. The impact of N-based acid rain on freshwaters will depend on the efficiency of drainage basins to retain the excess N. As long as forests retain N, no acidity is exported to downstream ecosystems. Researchers from the University of Waterloo are completing a three-year study on the mechanism of N retention in an upland Precambrian shield boreal forest. Forty kg N ha⁻¹ yr⁻¹ was added as NaNO₃ in 1995-96 to catchment U3 at the ELA. The added NO₃⁻ was labeled with the stable isotopes ¹⁵N and ¹⁸O to help trace the transformations and the location of storage of the retained N.

Catchment U3 efficiently retained the excess N (80%) during summer months, but less so during snowmelt when biological activity was low. Thus, on the short-term, excess N in precipitation can be a part of the ‘spring acid pulse’ observed in regions affected by elevated deposition of sulfuric acid. A survey in the spring of 1997 showed that most of the N retained by U3 was stored in organic soils, mosses, and lichens, but not in trees.

The internal cycling of N is remarkably heterogeneous within the upland boreal forest (Lamontagne *in press*). The high C:N ratio of the forest floor favors the immobilization of N in soil organic matter. However, the mineral soil underneath patches of mosses and lichens surrounding the forest have much lower C:N ratio and do not retain N as efficiently. Thus, the lower retention of N from lichen and moss-covered bedrock surfaces is not only due to rapid flushing of water and low plant biomass. High rates of nitrification under lichen patches promote the export of NO₃⁻.

Lamontagne, S. Nitrogen mineralization in upland Precambrian shield catchments: Contrasting the role of lichen-covered bedrock and forested areas. *Biogeochemistry* (in press).

6.1.1 Long-term N Deposition

In a related project, researchers from the University of Waterloo are reviewing the long-term N deposition record from the ELA. Of special interest, the ELA has the longest continuous record for the deposition of

particulate and dissolved organic N (DON) compounds in North America. Despite a ten-fold increase in the application of fertilizers and a two-fold increase in livestock farming in the Prairies, the deposition of NH_4^+ and NO_3^- has varied only between 2-6 kg N ha^{-1} yr^{-1} between 1970 and 1995. The peak in N deposition occurred during the late 1980's (10 kg N ha^{-1} yr^{-1}) during a period with warmer and drier conditions than usual. Most of the increase in N deposition was due DON. Little is known about the sources and the composition of DON in rain. Work on the possible sources for DON in rain at the ELA is underway.

6.2 Contribution of Forest Litterfall to Lake Nutrient Inputs

In conjunction with a catchment-scale study of the effectiveness of current Ontario forest harvesting buffer strip guidelines on fish habitat, P, N, and C inputs to lakes via litterfall from the forest edge were being measured at the Coldwater Lakes Experimental Watersheds (near Atikokan) and the Experimental Lakes Area in northwestern Ontario. This study was funded under the federal Sustainable Fisheries Initiative, which is ended in March, 1997.

At the ELA, P inputs from 100 year old and fire regeneration jack pine stands along the shores of Lake 239 were being investigated. In the summer of 1995, pans containing distilled water were set out in two pairs of transects from the water's edge to the centre of the lake, at distances of 0, 1, 3, 9, 30, 90, and 250 m from shore. Samples were collected at two-day intervals from mid-May to mid-October, and filtered through 1.2 μm filters. After identification of large particles, filters and filtrate were analysed for total P, N, and organic C. This work was continued in 1996, using the same techniques.

Litterfall collection began in the summer of 1995 at the Coldwater Lakes Experimental Watershed. No OMNR staff were available to do this collection at the Coldwater Lakes in 1996, and the work was discontinued at that site.

As of April 1997, the staff person carrying out this project was no longer with DFO. The project has been discontinued and many of the existing samples have not been fully analysed.

Note:

This summary was compiled by John Shearer, using information provided by research project leaders and other ELA staff. It is intended as an overview of research activities at the ELA during 1997. In most cases, the results provided are preliminary and subject to revision. For more detailed information, the reader should contact those researchers responsible for each study or refer to published literature.