

EXCELLENCE IN ECOLOGY

3

O. Kinne, Editor

Gene E. Likens

The Ecosystem Approach: Its Use and Abuse



Published 1992 by
Ecology Institute, W-2124 Oldendorf/Luhe
Germany

EXCELLENCE IN ECOLOGY

OTTO KINNE
Editor

3

Ecology Institute
Nymphenburgerstr. 11
D-80634 München
Germany

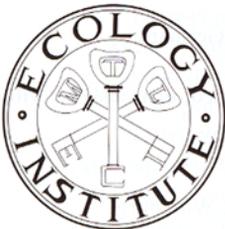
Gene E. Likens

THE ECOSYSTEM
APPROACH:
ITS USE AND ABUSE

Introduction (Otto Kinne)

Gene E. Likens: A Laudatio (William D. Williams)

3



Publisher: Ecology Institute
Nordbunte 23, W-2124 Oldendorf/Luhe,
Germany

Gene E. Likens

Institute of Ecosystem Studies
The New York Botanical Garden
Box AB, Millbrook, New York 12545-0129
USA

ISSN 0932-2205

Copyright © 1992, by Ecology Institute, W-2124 Oldendorf/Luhe, Germany

All rights reserved

No part of this book may be reproduced by any means, or transmitted, or translated without written permission of the publisher

Printed in Germany

Typesetting by Ecology Institute, Oldendorf

Printing and bookbinding by Konrad Triltsch, Graphischer Betrieb, Würzburg

Printed on low-chloride acid-free paper

Contents

<i>Introduction (O. Kinne)</i>	VII
<i>Gene E. Likens: Recipient of the Ecology Institute Prize 1988 in Limnetic Ecology. A Laudatio (W. D. Williams)</i>	XIX
Preface (G. E. Likens)	XXIII
I THE INCLUSIVE NATURE OF ECOLOGY	1
Defining Ecology	3
An Ecosystem Approach	9
From Organisms to Ecosystems	11
The Hubbard Brook Ecosystem Study	15
<i>Concluding Remarks</i>	16
II STYLE AND METHOD IN ECOSYSTEM ECOLOGY	17
(1) Approaches to the Study of Ecosystem Ecology	19
An Empirical or Natural History Approach	19
A Balance or Budgetary Approach	20
An Experimental Approach	21
A Comparative Approach	22
A Modeling or Computer Simulation Approach	23
<i>Concluding Remarks</i>	24
(2) Sustained Ecological Research	27
Examples from Ecosystem Science	29
The Hubbard Brook Ecosystem Study	29
Water	30
Lead	38
Sulfur	41
Base cations	45
Nitrogen	50
Animal populations in ecosystems	54
Lake ecosystems	55
Salt pollution	55
Eutrophication	57
Atmospheric Carbon Dioxide	60
Alternatives to Direct SER	62
<i>Concluding Remarks</i>	62

(3) Air-Land-Water Linkages and Interactions	63
Acid Rain	64
Toxic Metals	68
Mercury	68
Lead	69
Hydrologic Linkages	70
Stream ecosystems	71
Riparian zone linkages	81
Organic debris dams	84
Lake ecosystems	86
<i>Concluding Remarks</i>	88
III ECOSYSTEM ECOLOGY AND SOCIETY	89
(1) The Water Crisis	91
General Aspects	91
The Global Water Problem	92
The United States Water Problem	94
Pollution and Management Concerns	95
Nitrate contamination of aquatic resources	97
Animal wastes	100
Atmospheric deposition	101
Fertilizers	101
Deforestation	103
Industrial wastes	103
<i>Concluding Remarks</i>	103
(2) Environmental Issues, Scientific Communication and Ethics	105
The Premise	109
A Pattern	110
Scientific Communication and the News Media	117
<i>Concluding Remarks</i>	123
(3) Ecology, Ecosystems and Environmentalism	127
"Big" Science – The National Acid Precipitation Assessment Program	127
Human-Accelerated Environmental Change	136
Ecosystem Science and the Future	137
Environmentalism	138
Leap-Frogging Degradation	140
<i>Concluding Remarks</i>	142
IV EPILOGUE	143
Acknowledgements	145
References	147

Introduction

O. Kinne

Ecology Institute, Nordbunte 23, W-2124 Oldendorf/Luhe, Germany

In this introduction I outline the scope of the publication series “Excellence in Ecology”, and the structure and function of its publisher, the Ecology Institute (ECI). I also give the names of the ECI Prize Laureates, the respective quotations of the juries and the titles of their books as well as the names and jury quotations of the IRPE Prize (p. IX) Winners. I further list the names of the jury members who selected Gene E. Likens as our 1988 Laureate, and the names of the present scientific and technical ECI staff. Finally, I attempt to summarize the contents of this book and to highlight its essential messages.

Excellence in Ecology

Although still in its initial phase of existence, the publication series “Excellence in Ecology” (EE) has already received world-wide attention and applause. EE provides a platform for leading research ecologists – the recipients of the Ecology Institute Prize – to present overviews over their fields of professional competence, and to share with a large international readership their views on current ecological issues, as well as their insights into the ecological realities that form the framework for human existence.

Published by the Ecology Institute (ECI) in Oldendorf/Luhe (Germany), EE books address fellow scientists, teachers and students, as well as managers, politicians and other decision makers who must translate scientific ecological information into practicable rules and laws for the benefit of nature and for securing the very basis for the development and survival of modern human societies. In this way, EE books support and elaborate on ECI’s aims (see below). EE books are available worldwide at cost price.* They may also be donated to scientific libraries in Third-World countries.

* Address book orders to Ecology Institute, W-2124 Oldendorf/Luhe, Germany (Tel. 04132/7127; Fax 04132/8883). For book authors, titles and prices consult pp. X–XII

The Ecology Institute

The international Ecology Institute (ECI), located some 55 km south of Hamburg (Germany) in the small village of Oldendorf/Luhe, was founded in 1984. It is funded by Inter-Research, the publisher of the three international scientific journals “Marine Ecology Progress Series”, “Diseases of Aquatic Organisms” and “Climate Research”. The ECI is a non-profit-making organisation. At present, the institute has a scientific staff of 43 ecologists (see below) – all of outstanding professional reputation. Neither the director nor any of the scientific staff members receive remuneration.

Scientific ECI members are recruited world-wide among leading ecologists. Nominations for ECI membership (to be addressed to ECI’s director) are welcome. It now has become a tradition that ECI Prize winners are invited to join the institute’s staff. This provides for “fresh blood”, assures a high level of expertise and, in regard to selecting Laureates, strengthens impartiality (prize winners are excluded from future nominations).

The ECI strives to (1) further the exchange of information between marine, terrestrial and limnetic ecologists, and promote advancement in environmental research; (2) compensate for the lack of balance between analyzing and synthesizing research efforts and thus help to provide more feedback and critical overview for biological sciences; (3) draw the attention of scientists, administrators, politicians and the general public to important issues resulting from ecological research; (4) assist in finding a long-term compromise between the increasingly destructive potential of modern industrial societies and the need for defining and applying measures to protect nature, commensurate with achieving and sustaining the highest possible living standard for human societies. ECI’s aims and activities have been outlined more fully in the introduction to Book 1.

At present, the ECI’s major means of approaching these aims are the two international prizes (ECI Prize, IRPE Prize; see below) conferred annually by the institute. While there are several international prizes offered now in ecology, the ECI Prize is unique for two reasons: (1) it was established and is financed by research ecologists; (2) the prize gives and takes: it both honors the recipient and provides a stipend, and it expects the Laureate to serve science by authoring an EE book taking into account ECI’s aims.

The ECI also supports, via the Otto Kinne Foundation (OKF)*, promising young environmental scientists in eastern European countries – especially in the fields of ecology, diseases of animals, plants and microorganisms, and climate research. The OKF aids postgraduates – without

distinction of race, religion, nationality or sex – by providing financial assistance for professional travel and/or scientific equipment. For details write to the ECI.

In an annually rotating pattern, ECI Juries select marine, terrestrial or limnetic ecologists to receive the Ecology Institute Prize, which carries a stipend of US \$ 5000, and the IRPE Prize (International Recognition of Professional Excellence), which carries a stipend of US \$ 750. ECI Juries also select postgraduates to receive OKF Fellowships.

While the ECI Prize honors a research ecologist distinguished by sustained excellent achievements, the IRPE Prize honors a young (not more than 40 years of age) research ecologist who has conducted and published uniquely independent, original and/or challenging research representing an important scientific breakthrough, and/or who must work under particularly difficult conditions.

Nominations for ECI and IRPE Prizes (accompanied by CV, list of publications and a statement why, in the opinion of the nominator, the nominee qualifies for the prize) are invited from research ecologists on a global scale. They should be sent to the chairperson of the respective ECI Jury, or alternatively to ECI's director who will then forward them to the chairperson. Eligible are all ecologists engaged in scientific research (except ECI's director, the Jury's chairperson, and previous Laureates; Jury members nominated will be replaced by other ECI members). The Jury selects prize winners using the nominations received as well as their own knowledge of top performers and their own professional judgement.

Nominations for OKF Fellows, addressed to the ECI and accompanied by a letter of support as well as a documentation of the nominees' performance, are invited from ECI members and members of the Editorial Staff of the three international Inter-Research journals. The first Fellows will be selected by an ECI Jury in 1993.

* Named after its sponsor, Professor Otto Kinne, the foundation is endowed with an initial fund of DM 200 000. Foundation rules provide for objectivity in OKF Fellow selection and for rigid control of cash flows. The ECI invites other sponsors to follow this example. Sponsors are entirely free to determine area and scope of their foundation (within the realms of biological and environmental sciences). All administrative costs are covered by the ECI; hence 100 % of the money dedicated will be spent for the purpose intended. The highly qualified ECI staff and Editorial Board members of Inter-Research journals assure critical and careful selection of fellows, and the ECI's world-wide activities guarantee immediate global effectiveness and visibility of any new foundation

ECI Prize Winners, Their Major Scientific Achievements and Their Books

Tom Fenchel (Helsingør, Denmark), ECI Prize winner 1986 in marine ecology.

Quotation of the Jury (Chairman: John Gray, Oslo, Norway)

The Jury found Professor T. Fenchel's contribution to ecological knowledge in a variety of research fields to be of the highest international class. In particular, the Jury cites his brilliant and uniquely important studies on the microbial loop which have opened up a fundamentally new research field. Professor Fenchel is, in addition, an excellent publicizer in his field of research with authorship of a number of standard works in marine ecology.

Book 1: Ecology – Potentials and Limitations. (Published 1987; price DM 67 plus DM 5 for postage and handling)

Edward O. Wilson (Cambridge, MA, USA), ECI Prize winner 1987 in terrestrial ecology.

Quotation of the Jury (Chairman: Sir Richard Southwood, Oxford, UK)

Professor E. O. Wilson is distinguished for his many contributions to different aspects of ecology and evolutionary biology. His life-time love of Nature, a theme explored in his book "Biophilia", has been particularized in his study of ants leading to major new insights on the evolution of castes and the operation of social systems. His seminal "Sociobiology", derived from this work, has founded a new branch of science, between ecology and the social sciences. With the late Robert MacArthur he was the originator of the modern theories of island biogeography that have contributed not only to the understanding of island biota, but to community and population ecology.

Book 2: Success and Dominance in Ecosystems: The Case of the Social Insects. (Published 1990; price DM 49 plus DM 5 for postage and handling)

Gene E. Likens (Millbrook, NY, USA), ECI Prize winner 1988 in limnetic ecology.

Quotation of the Jury (Chairman: William D. Williams, Adelaide, Australia)

Gene Likens is a distinguished limnologist who has made salient contributions to many fields of limnology. In 1962 he initiated and developed (with F. H. Bormann) the Hubbard Brook Ecosystem Study in New Hampshire.

Comprehensive investigations in this study provided a model for ecological and biogeochemical studies worldwide. A major finding of the study was that rain and snow are highly acidic. "Acid rain" is now recognized as one of the major environmental hazards in North America, Europe and elsewhere. Elected to the American Academy of Sciences in 1979, and the National Academy of Sciences in 1981, Gene Likens is a highly worthy recipient of the 1988 ECI Prize in Limnetic Ecology.

Book 3: The Ecosystem Approach: Its Use and Abuse. (Published 1992; price DM 59 plus DM 5 for postage and handling)

Robert T. Paine (Seattle, WA, USA), ECI Prize winner 1989 in marine ecology.

Quotation of the Jury (Chairman: Tom Fenchel, Helsingør, Denmark)
Robert T. Paine has made substantial and original contributions to marine biology and to ecology in general. In particular the Jury mentions the discovery of the role of patch formation and properties of food web structure in shaping communities of sedentary organisms. These studies (of which several have become classics of marine ecology) have fundamentally changed the way in which we view marine benthic communities. This work has also served as an inspiration for innovation in the mathematical description of community processes and has had a lasting impact on our understanding of "landscape dynamics", of equal importance to the development of the science of ecology and to conservation ecology.

Book 4: Ecological Pattern and Process on Rocky Shores. (To be published 1992)

Harold A. Mooney (Stanford, CA, USA) ECI Prize winner 1990 in terrestrial ecology.

Quotation of the Jury (Chairman: John L. Harper, Penmaenmawr, UK)
Professor Harold A. Mooney is distinguished for his studies of the physiological ecology of plants, especially of arctic-alpine and mediterranean species. He has explored the ways in which plants allocate carbon resources and expressed this allocation in terms of costs, benefits and trade-offs. This has given a quantitative dimension to the study of plant-animal interactions and acted to integrate physiological ecology with population biology, community ecology, and ecosystem studies.

Book 5: The Globalization of Ecological Thought. (To be published 1993)

Robert H. Peters (Montreal, PQ, Canada), ECI Prize winner 1991 in limnetic ecology.

Quotation of the Jury (Chairman: Jürgen Overbeck, Plön, Germany)

Professor R. H. Peters' contributions to the fields of limnology and ecology have been numerous and far reaching. His work on phosphorus cycling in lakes provides examples of excellent research illuminating a number of important aspects regarding the movement and availability of phosphorus in aquatic systems. His book "The Ecological Implications of Body Size" gives a powerful overview of the utility of allometric relationships for the study of ecological problems and for building ecological theory.

Book 6: Science and Limnology. (Tentative title; to be published 1994.) Authors: The Late F. H. Rigler and R. H. Peters

IRPE Prize Winners and Their Major Scientific Achievements

Colleen Cavanaugh (The Biological Laboratories, Harvard University, Cambridge, MA 02138, USA), IRPE Prize winner 1986 in marine ecology.

Quotation of the Jury (Chairman: John Gray, Oslo, Norway)

The Jury found the research of Dr. C. Cavanaugh on chemosynthesis – initially concerning hot-vent fauna but extended to other sulphide-rich habitats – to be highly original and to represent a major scientific breakthrough. Her hypothesis, formulated whilst a beginning graduate student, met severe opposition from established scientists with opposing views, but nevertheless proved to be correct. The Jury acknowledge Dr. Cavanaugh's brilliant and independent research in understanding chemosynthetic energetic pathways.

Karel Šimek (Hydrobiological Institute, Czechoslovak Academy of Sciences, 370 05 České Budějovice, Czechoslovakia), IRPE Prize winner 1990 in limnetic ecology.

Quotation of the Jury (Chairman: Jürgen Overbeck, Plön, Germany)

Dr. Karel Simek belongs to the generation of young limnologists in Eastern Europe who – despite lack of international information exchange – published, under difficult conditions, excellent contributions to the field of Aquatic Microbiology. He enjoys a high international reputation. Under the present, improved conditions Simek is likely to proceed even more successfully to new professional horizons.

Ecology Institute Jury 1988 for the Field of Limnetic Ecology

Recruited from the institute's scientific staff, jury members are appointed by ECI's director. They elect among themselves the chairperson.

Professor W. D. WILLIAMS (Chairman), Department of Zoology, The University of Adelaide, GPO Box 498, Adelaide, South Australia 5001

Professor J. I. FURTADO, 19 Langford Green, Champion Hill, London SE5 8BX, England

Professor S. D. GERKING, Department of Zoology, Arizona State University, Tempe, Arizona 85281, USA

Professor J. E. HOBBIÉ, Marine Biological Laboratory, The Ecosystems Center, Woods Hole, Massachusetts 02543, USA

Professor K. LILLELUND, Institut für Hydrobiologie und Fischereiwissenschaften, Olbersweg 24, W-2000 Hamburg 50, Germany

Professor R. MARGALEF, Department d'Ecologia, Facultat de Biologia, Universitat de Barcelona, Avgd. Diagonal 645, E-08028 Barcelona, Spain

Professor E. PATTÉE, Département de Biologie Animale et Ecologie, Université Claude Bernard, Lyon I, 43, Bd. du 11 Novembre 1918, F-69622 Villeurbanne Cedex, France

I am grateful to the jury and its chairman Professor W. D. Williams for their critical work. Several other outstanding ecologists nominated for the prize were also considered highly eligible, and the final decision was difficult to make.

Ecology Institute Staff 1991 (in brackets: year of appointment)

Director and Founder: Professor O. Kinne, W-2124 Oldendorf/Luhe, Germany

Marine Ecology

Dr. F. Azam, La Jolla, CA, USA (1985)

Prof. H.-P. Bulnheim, Hamburg, Germany (1984)

Prof. J. D. Costlow, Beaufort, NC, USA (1984)

Prof. T. Fenchel, Helsingør, Denmark (1985)

Dr. N. S. Fisher, Upton, NY, USA (1985)

Prof. J. Gray, Oslo, Norway (1984)

Prof. B.-O. Jansson, Stockholm, Sweden (1989)

Dr. G. I. Müller, Constanta, Romania (1988)

Prof. E. Naylor, Bangor, UK (1984)
 Prof. S. W. Nixon, Narragansett, RI,
 USA (1989)
 Prof. R. T. Paine, Seattle, WA, USA
 (1990)
 Dr. T. Platt, Dartmouth, Canada (1984)

Acad. Prof. G. G. Polikarpov, Sev-
 astopol, Ukraine (1985)
 Dr. T. S. S. Rao, Bambolim, India
 (1985)
 Acad. Prof. A. Zhirmunsky, Vladivos-
 tok, Russia (1988)

Terrestrial Ecology

Prof. T. N. Ananthakrishnan, Madras,
 India (1984)
 Prof. F. S. Chapin, III, Fairbanks, AK,
 USA (1986)
 Prof. J. Ehleringer, Salt Lake City, UT,
 USA (1986)
 Prof. M. Gadgil, Bangalore, India
 (1985)
 Prof. J. L. Harper, Bangor, UK
 (1986)
 Prof. E. Kuno, Kyoto, Japan
 (1986)
 Prof. A. Macfayden, Coleraine, UK
 (1985)

Prof. H. A. Mooney, Stanford, CA,
 USA (1991)
 Prof. H. Remmert, Marburg, Germany
 (1985)
 Dr. M. Shachak, Sede Boker Campus,
 Israel (1989)
 Acad. Prof. V. E. Sokolov, Moscow,
 Russia (1986)
 Prof. Sir R. Southwood, Oxford, UK
 (1986)
 Prof. S. Ulfstrand, Uppsala, Sweden
 (1986)
 Prof. E. O. Wilson, Cambridge, MA,
 USA (1988)

Limnetic Ecology

Prof. J. I. Furtado, Washington, DC,
 USA (1985)
 Prof. S. D. Gerking, Tempe, AZ, USA
 (1986)
 Prof. J. E. Hobbie, Woods Hole, MA,
 USA (1986)
 Prof. G. E. Likens, Millbrook, NY,
 USA (1989)
 Prof. K. Lillelund, Hamburg, Germany
 (1985)
 Prof. R. Margalef, Barcelona, Spain
 (1986)
 Prof. J. Overbeck, Plön, Germany
 (1984)

Prof. T. J. Pandian, Madurai, India
 (1985)
 Prof. E. Pattée, Villeurbanne, France
 (1987)
 Prof. T. B. Reynoldson, Bangor, UK
 (1985)
 Prof. J. G. Tundisi, Sao Paulo, Brazil
 (1990)
 Dr. D. Uhlmann, Dresden, Germany
 (1989)
 Prof. W. Wieser, Innsbruck, Austria
 (1987)
 Prof. W. D. Williams, Adelaide,
 Australia (1986)

Technical Staff (all Oldendorf/Luhe, Germany)

J. Austin
 G. Bendler
 M. Bruns
 C. Fesefeldt
 R. Friedrich
 B. Fromm

J. Hunt
 H. Kinne
 F. Nebe
 R. Stedjee
 H. Witt

Book 3: The Ecosystem Approach: Its Use and Abuse

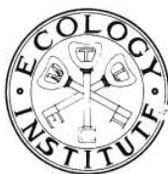
The author of EE Book 3, Gene Elden Likens, is the recipient of the ECI Prize in limnetic ecology 1988. The ECI Jury 1988 (see above) have formulated the excellent research performance that won Gene E. Likens the prize in a quotation which is reproduced on pp. X–XI and stated in the prize awarding document, illustrated on p. XVI.

In his book, Gene E. Likens spans a wide conceptual arch. Beginning with a description and definition of his subject, he explains and discusses how to approach ecological problems, emphasizes the need for sustained (long-term) ecological studies and ends with a critical assessment of the interrelations between ecology on the one hand and the activities, needs and failures of human groups and societies on the other.

Elaborating and expanding on earlier definitions, Likens defines ecology as “the scientific study of the processes influencing the distribution and abundance of organisms, the interactions among organisms and the transformation and flux of energy and matter”. He emphasizes, and rightly so, the interactive role of experimentation, system integration and synthesis. Likens sees the ultimate goal of ecology in working out an encompassing synthetic – not a fragmented – view of nature.

Approaches for studying ecosystem ecology are seen to include empirical or natural-history studies, analyses of balances and budgets, experimentation, comparative assessments, and modeling or computer simulations. It is the combined application of these approaches that provides a solid basis for critical analysis, for comprehension of the mind-boggling complexity of natural ecosystems, and for providing useful information to environmental managers and decision makers.

Based on a pace-setting scientific concept which he planned and executed together with F. H. Bormann – the comprehensive long-term Hubbard Brook Ecosystem Study – Gene E. Likens exemplifies and underlines the significance of sustained ecological research. World-wide we encounter difficulties in assessing the agents, dimensions and consequences of ecological change, not least because we lack base-line data against which to gauge our measurements and observations. But how else can we distinguish among natural variabilities, “normal” periodicities and actual net changes? Likens has identified sustained ecological research as “a critical need” in ecological analyses. Long-term studies – there are still only very few of them – have revealed that short-term measurements and observations may be misleading and that



ECOLOGY INSTITUTE PRIZE 1988

In Limnetic Ecology

Professor Gene E. Likens

has been elected by the Limnetic Ecology Jury of the Ecology Institute (ECI)
as the winner of the 1988

ECOLOGY INSTITUTE PRIZE

Gene Likens is a distinguished limnologist who has made salient contributions to many fields of limnology. In 1962 he initiated and developed (with F. H. Bormann) the Hubbard Brook Ecosystem Study in New Hampshire. Comprehensive investigations in this study provided a model for ecological and biogeochemical studies worldwide. A major finding of the study was that rain and snow are highly acidic. 'Acid rain' is now recognized as one of the major environmental hazards in North America, Europe and elsewhere. Elected to the American Academy of Sciences in 1979, and the National Academy of Sciences in 1981, Gene Likens is a highly worthy recipient of the 1988 ECI Prize in Limnetic Ecology.

Limnetic Ecology Jury ECI:

Professor W. D. Williams, Adelaide, Australia
(Chairman)

Professor J. I. Furtado, London, United Kingdom
Professor S. D. Gerking, Tempe, USA

Professor J. E. Hobbie, Woods Hole, USA
Professor K. Lillelund, Hamburg, FRG
Professor R. Margalef, Barcelona, Spain
Professor E. Pattée, Villeurbanne, France

ECOLOGY INSTITUTE

The Director



Professor Dr. Otto Kinne

Oldendorf/Luhe, Federal Republic of Germany, March 1, 1989

only sustained measurements over decades may reveal net trends in ecosystem changes.

At Hubbard Brook, sustained ecological research, in combination with the ecosystem approach, has revealed important new insights into ecosystem functions, such as evapotranspiration, dry deposition, and weathering – parameters that are difficult to quantify in ecosystems.

Linkages and interactions are key factors which determine and direct ecological relationships, and they are crucial for ecological management. An important linkage between ecosystem and biosphere is the transport of materials to places remote from the emission source. Such transport interactions must be recorded and analyzed not least in the evaluation and management of pollutant effects. Hydrological and biogeochemical linkages may be of great importance in context with global climate change. “These linkages are enormously complex, and trying to understand them is one of the biggest scientific challenges today” (p. 88).

Additional major focal points addressed by Gene E. Likens are the water crisis, the relation between ecological science and other human activities such as environmental engagement by ethically and/or politically motivated groups, the role of the news media, and the ecology-related actions of managerial and political decision makers.

The provision of water suitable for human consumption, domestic use and food production (agriculture, aquaculture) is rapidly developing into one of our gravest environmental problems. First recognized and presented for professional and public discussion, at the time with deplorably little echo, by the German limnologist August Thienemann (Plön) in the 1950s, the water crisis is now attaining dramatic proportions and still continues to gain momentum as a function of increases in world-wide human population growth, in energy requirements per capita, and in environmental pollution (as well as the likelihood of detrimental world-wide climate changes). Possibilities for immediate improvement of the situation include water conservation, desalination, and ice melting – the latter two requiring huge amounts of energy. Conservation could be practised in terms of efficient irrigation, prevention of water supply leakages, water-efficient land-



Ecology Institute Prize 1988 in the field of limnetic ecology. Reproduction of the prize awarding document

scaping, and water-efficient toilets* and showers. World-wide climate changes may in the foreseeable future lead to significant rises in sea level and increasing storm activities; both would cause salt-water flooding of vast areas of low-lying land and of major cities, and thus augment the water crisis as well as other environmental problems and hazards.

While ecological research has documented and analysed the progressive change and degradation of our environment, translation of the knowledge produced into sensible and effective managerial and political consequences has thus far not been particularly successful. Nevertheless, acid rain, the ozone hole, deforestation, global climate change, toxic wastes, ocean dumping and eutrophication have become important issues in the news media and have alerted sections of the general public. This has resulted in considerable pressure on legislators and environmental managers to initiate appropriate actions. It now has become very clear that we must search for a compromise between ecology and economy. As Likens puts it: “Environmental health is . . . not inconsistent with economic imperatives and political realities. In fact, a healthy environment is the basis for a healthy economy” (p. 144).

The author concludes his book by saying that human-induced environmental degradation is not inevitable – it’s simply cheaper and easier. For assessing the health status of our environment, and for prescribing protective or therapeutic measures, ecological research is – and remains – the basic tool. We need more such research and we need improved mechanisms for adequately responding to critical findings.

Gene E. Likens utilizes his unique personal insight into ecosystem functions and structures with a keen sense of critical, systematic inquiry and ethical responsibility. He elucidates for us – professionals and laymen alike – the instrumentarium of modern ecology. He explains and demonstrates what it can do. And he outlines what in his opinion must be done to avoid, or reduce, damage to our planet.

* I am writing this in Kenya while visiting scientific institutions. In Mombasa the water crisis has escalated so much that water-efficient toilets have just been promoted to no-water toilets

Gene Elden Likens: Recipient of the Ecology Institute Prize 1988 in Limnetic Ecology. A Laudatio

W. D. Williams

Department of Zoology, University of Adelaide, GPO Box 498,
Adelaide, 5001, Australia

Sadly but truly, modern science is such a comprehensive, complex endeavour that scientists must now devote every available minute to their profession merely to keep abreast of developments. To advance the frontiers of science, they must devote all their remaining minutes! As Alice said in *Through the Looking Glass*: “it takes all the running you can do to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!”. Add a variety of hurdles to this race (constraints of space, grants, students, equipment . . .), and the outcome is predictable: many better-known scientists are aggressively competitive, single-minded, rather selfish individuals whose image one cannot fail to admire at a distance – but at a distance.

Perhaps surprisingly, however, my experience is that very few truly great scientists actually fall into this mould. Gene E. Likens, limnologist *extraordinaire*, certainly does not. A scientist of the first rank, his journey to that position has *not* altered his self-effacing, kindly and modest demeanour *en route*. Steel he has, of course, and naive he is not: but the essential Likens *is* the sort of individual one *can* admire from close quarters without risk of damage to the image! He is a thoroughly likeable fellow whom I’m privileged to know and for whom the writing of this laudatio is a pleasure. I hope these remarks do not unduly embarrass him (but suspect they will).

I raise this aspect first because a laudatio for a scientist often leaves one with a clear indication of scientific accomplishments, a specific knowledge of awards, and a memory of the subject’s career – but rarely with any feeling for a *la statue interieure* (perhaps sometimes the omission is intentional!). It would have been a great pity if this laudatio had not attempted to provide at least an inkling of Gene’s “inner statue”: his humanity.

Gene Elden Likens was born in Pierceton, Indiana, USA, in 1935. After school he was an undergraduate (B.S.) at Manchester College (1955–1957), then a postgraduate (M.S., Ph.D.) at the University of Wisconsin, Madison (1957–1962). His major subject at both institutions was zoology. Subsequently, he spent seven years on the Faculty of Dartmouth College before joining Cornell University, where he eventually became Chairman of the Section of Ecology and Systematics. Since September 1983 he has been the Director of the Mary Flagler Cary Arboretum, Millbrook, New York. Concurrently, he is Vice-President of The New York Botanical Garden, Bronx, New York, Adjunct Professor at Cornell University, Professor at Yale and Rutgers Universities, and Fellow of Timothy Dwight College, Yale University. He has been an executive in several learned societies (*inter alia*, president of both the Ecological Society of America and the American Society for Limnology and Oceanography), and an advisor to many government committees.

During his career he has received many honours and awards. He was elected to the American Academy of Sciences in 1979, to the National Academy of Sciences in 1981, and to the Royal Swedish Academy of Science (Foreign Member) in 1988. Honorary Doctorates have been awarded by Manchester College, Rutgers University, Plymouth State College of the University System of New Hampshire, Miami University, and Union College. He received the American Motors Conservation Award in 1969, the first G. E. Hutchinson Award for excellence in research from the American Society for Limnology in 1982, the U.S. Forest Service 75th Anniversary award for significant contributions to forestry and conservation science in 1986. Not least, of course, he is the recipient of our ECI Prize in Limnetic Ecology (awarded 1988).

His research career began with research on physical limnology, particularly water circulation and heat budgets in lakes. Meromictic lakes were an early interest. The use of radio-isotopes to study water-circulation and biological transport in lakes was also an early research interest.

In 1963, together with F. H. Bormann, he began the Hubbard Brook Ecosystem Study, the first truly comprehensive attempt to set up controlled experiments involving whole ecosystems. The attempt was enormously successful and became the model for other whole ecosystem studies.

In short, the Hubbard Brook Ecosystem Study was an in-depth ecosystem analysis. It integrated long-term data on precipitation and stream-water chemistry, hydrology and weathering, and considered the dynamics of atmospheric gases and water within the system. The study showed how the

Hubbard Brook ecosystem (an area of second-growth northern hardwood forest in New Hampshire) moderates and changes inputs, and how its outputs affect biogeochemical cycles.

An important element of the Hubbard Brook study was its long-term nature: and it was this very feature which enabled Likens to document for the first time in the United States the existence and impact of acid rain. His subsequent research on acid rain has been seminal and has helped focus attention on the global nature of many other environmental problems. The importance of long-term ecological studies and of whole-lake studies, the nature of biogeochemical cycles, and the chemical nature of atmospheric precipitation continue to be important research directions for him.

Not least amongst his scientific achievements, albeit personally indirect, has been the creation of a first-rate scientific institute at Millbrook dedicated to three goals: the pursuit of ecological research relevant to the understanding and management of natural ecosystem, the establishment and maintenance of long-term, experimental reference studies of ecosystems; and the support of educational and community needs with regard to ecological awareness.

At Millbrook, his perception of what provides the most favourable framework for important and innovative science to proceed has already borne fruit. One venture alone, the 'Cary Conferences' (commenced 1985), provided a unique opportunity for major issues in ecology to be discussed and their published proceedings have already had a major impact on ecological teachings.

Truly an outstanding aquatic ecologist, Professor G. E. Likens is a most worthy recipient of the ECI Prize in Limnetic Ecology.

Preface

It is flattering to win a prize or to receive recognition from your peers, but with the ECI Prize comes the harsh reality of accepting the responsibility to write a book (I suppose to justify that you should have been selected for the Prize in the first place!). Writing a book is very difficult work – at least for me – but the “Excellence in Ecology” book offers an unusual opportunity to advance some ideas and to make some statements in a way not normally provided in science. I have chosen to focus my book on ecosystems, because I find this approach to the unraveling of ecological complexity productive, satisfying and fun. I believe that the ecosystem concept provides a valuable framework for integrating studies of the relationships among individuals, populations, communities and their abiotic environments.

I have applied the ecosystem approach in cooperation with numerous colleagues during the last 30 years or so, to studies of lakes, streams and forests, particularly those of the Hubbard Brook Valley in New Hampshire, USA. I will draw heavily on these studies for the data and examples used in this book. After collecting masses of data during all these years, I still have more questions than answers, but I want to share some of these questions, as well as some answers, with the readers of this book in the hope that others will help unravel the complexity exposed by these previous efforts. Large-scale units of ecological interaction are mind-boggling in diversity and complexity. Nevertheless, this complexity provides both the challenge and the excitement of discovery from pursuing ecological understanding.

I begin the book with a discussion about the inclusive nature of ecology and propose a new, overarching definition for this rapidly expanding discipline. This discussion is intended to provide the context for a description of the concepts and approaches that are used in pursuit of ecosystem ecology, as well as to provide a backdrop for comparisons with environmentalism. Sections 2 and 3 in Chapter II provide examples of ecological information, largely obtained from sustained research and integrated at the level of an ecosystem. Chapter III addresses (i) major environmental problems, (ii) stresses between science and politics, (iii) conflicts between big science efforts and investigator-initiated research, and (iv) fundamental differences between environmentalism and professional ecology.

A relatively large proportion of this book is devoted directly or indirectly to environmental problems and management concerns. I use this opportunity to address some of the important scientific aspects related to these issues and to express some thoughts about scientific communication, about decision making, and about ethics. My comments are from the perspective of an American scientist utilizing the ecosystem approach.

Millbrook, New York, USA, November 1991

Gene E. Likens

I

THE INCLUSIVE NATURE OF ECOLOGY

Defining Ecology

“One goes to Nature only for hints and half-truths. Her facts are crude until you have absorbed them or translated them. . . . It is not so much what we see as what the thing seen suggests.”

John Burroughs
[*Signs and Seasons* (1886)]

In my view, the *ultimate* challenge for Ecology is to integrate and synthesize the ecological information available from all levels of inquiry into an understanding that is meaningful and useful to managers and decision makers. It frequently will not be possible a priori to know which or when new ecological information will be useful to managers of natural resources, but nevertheless this remains as an ultimate goal.

Indeed, the discipline of ecology embraces a continuum of ideas, concepts and approaches, from organismal biology (e.g. systematics, physiology, genetics) at one end of the spectrum to geology, hydrology, and meteorology at the other (Fig. 1). Attempts to synthesize understanding from interactions between organisms (biotic components), from interactions between organisms and their abiotic environments, and from the interplay between both of these, however, are what make ecology unique (Berry 1989) among sciences. Such interactions between organisms might include predation of bacterioplankton by zooplankton, or competition between individual bacteria, or between bacterioplankton and phytoplankton for nutrients. Interactions can occur on many temporal and spatial scales and include such diverse forms as life cycles of parasitic organisms, coevolution of species, cycling of nutrients, food web dynamics, eutrophication of a lake, atmospheric pollution of a landscape, etc. Factors determining spatial and temporal patterns – e.g. branching of a tree, cycles of abundance or growth, distribution of populations, ecotones, community diversity, and landscape mosaics – are also important focal points of ecological research. Another obvious hierarchy for ecological approaches is the spatial scale of the ecological process or phenomenon being considered, e.g. from the atomic scale to

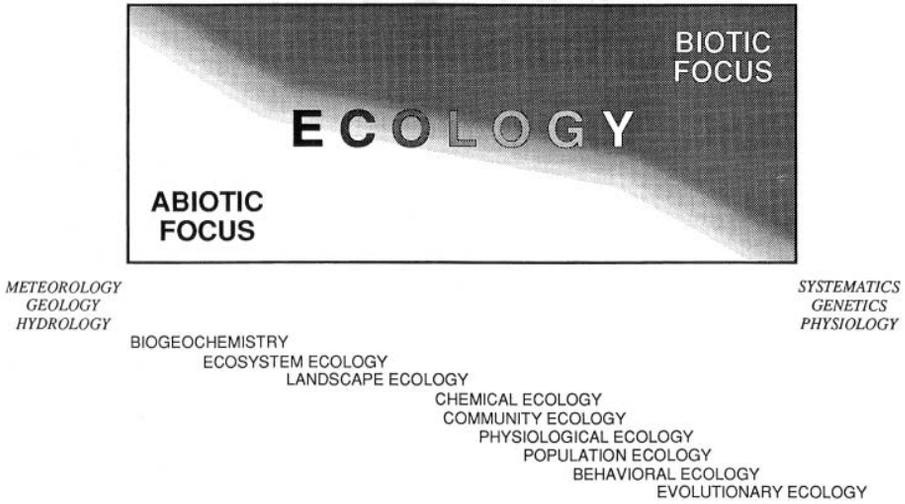


Fig. 1. Ecological studies range from those focused on more abiotic relationships to those focused on more biotic relationships. Ecology, as represented by the box in this illustration, is softly bounded on one end of this spectrum by disciplines such as meteorology, geology and hydrology, and on the other end by systematics, genetics and physiology. The spectrum ranging from more abiotic to more biotic ecological subdisciplines then might include from left to right, biogeochemistry, ecosystem ecology, landscape ecology, chemical ecology, community ecology, physiological ecology, population ecology, behavioral ecology, evolutionary ecology. Obviously, the abiotic-biotic focus is only one of the dimensional axes for subdisciplines in ecology. Another axis is the spatial or temporal scale of the ecological process or phenomenon being considered, e.g. landscape vs. organism

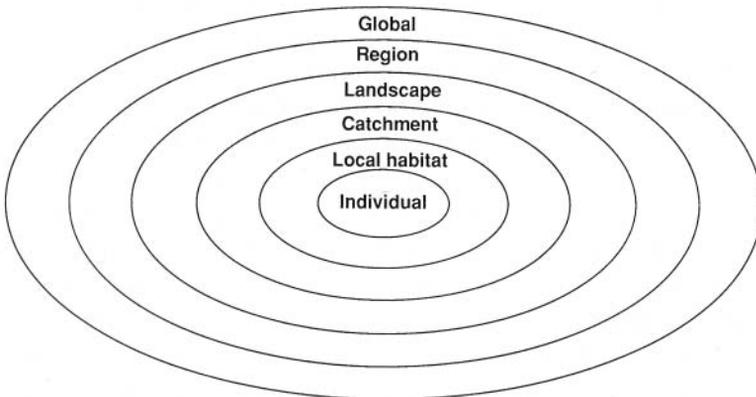


Fig. 2. Spatial scales of consideration commonly used in different ecological approaches

the scale of the universe (Fig. 2), making holism and reductionism a point of view. That is, from the viewing point of whether answers are sought by looking upward or downward along some spatial scale of organization or conceptualization.

The first volume (Fenchel 1987) in the series “Excellence in Ecology” began with a discussion about the definition of ecology. Fenchel stated in his preface that his book was written “. . . to engage (ecologists) in a debate on the definition of ecology.” Indeed, I believe that it is important to revisit the question: What is ecology? There are two definitions of ecology in wide use in the United States today:

- “The scientific study of the distribution and abundance of organisms” (Andrewartha 1961)¹
- “The study of the relation of organisms or groups of organisms to their environment” (Odum 1959, 1971)²

These definitions are different in concept and intent. The first connotes a descriptive science and focuses on organisms; the second puts more stress on interactions and on environmental factors, but is vague. These definitions are the result of, and in some instances have produced, two very different approaches to the study of ecological pattern, diversity and complexity. These developments have tended to produce an intellectual schism within the discipline.

Traditionally most ecologists have been trained as biologists with research focused on the activities of and interactions between organisms (McIntosh 1985). An example would be to study the distribution and dynamics of a population of a defoliating insect. Such ecologists most likely would subscribe to some version of Andrewartha’s definition (e.g. Krebs 1972, Fenchel 1987).

During the past 30 years or so, particularly following the stimulation provided to ecologists interested in ecological systems by the second edition of Odum’s textbook on *Fundamentals of Ecology* (1959), by Vernadsky’s

¹ A major ecological textbook authored by Andrewartha and Birch (1954) some seven years earlier had a title similar to Andrewartha’s definition

² Odum stated that ecology is usually defined in this way, but believed that a more modern definition should be “the study of the structure and function of nature” (1959, p. 4)

(1944, 1945), Hutchinson's (1950, 1957) and Redfield's (1958) efforts in biogeochemistry, and by experimental manipulations of entire ecosystems (Juday and Schloemer 1938, Hursh et al. 1942, Hasler et al. 1951, Likens 1985c), there has been a growing research focus on the role of abiotic factors, such as geologic, chemical, hydrologic, and meteorologic factors. An example would be to study the effects on nutrient cycling of the population dynamics of a defoliating insect. Ecologists emphasizing the role of such abiotic factors in attempting to understand the structure, function and succession or development of communities and ecological systems would tend to favor some version of Odum's (1971) definition. Obviously, scientists subscribing to either definition would evaluate the role of both biotic and abiotic regulation, but it is the goal and emphasis of the research that are different.

Ernst Haeckel's (1866) original definition of ecology, although focused on animals, was embracing and straightforward:

By ecology we mean the body of knowledge concerning the economy of nature – the investigation of the total relations of the animal both to its inorganic and to its organic environment; including above all, its friendly and inimical relations with those animals and plants with which it comes directly or indirectly into contact.

Because creative scientists want to pursue questions that they believe are scientifically important and because they want identity and visibility from their work, a large variety of ecological specialties or subdivisions have developed since 1866, e.g. autecology, population ecology, chemical ecology, evolutionary ecology, physiological ecology, plant ecology, aquatic ecology, applied ecology, paleoecology, community ecology, ecosystem ecology, landscape ecology and global ecology. In fact, such specialization is inevitable and appropriate, as these adjectives attempt to describe what ecologists actually do within this richly diverse field, but represents, nevertheless, a severe fractionation regarding the overall inclusive and integrative nature of ecology. Hairston, Sr. (1991) has opined that this specialization in ecology is due in part to the inability of ecologists to read and digest the huge explosion of published materials in recent decades.

Such pluralism is carried to the extreme in popular additions of focus to the discipline of ecology as well, as in "child ecology", "deep ecology", "body ecology" (McIntosh 1990), "industrial ecology" (Hicks 1991), "spiritual ecology" and "human ecology". The word, ecology, even has become a registered US trademark of a paper company, and is used on writing

pads. In my opinion, this fractionation of the field and popular debasing of the scientific concept has reduced the overall effectiveness of ecology to be integrative and synthetic.

In its worst form this specialization and fractionation might have the biologically orientated ecologists focusing on interactions between species (e.g. competition for nitrogen) within an environment of “chemicals”, whereas biogeochemically orientated ecologists might focus on geochemical

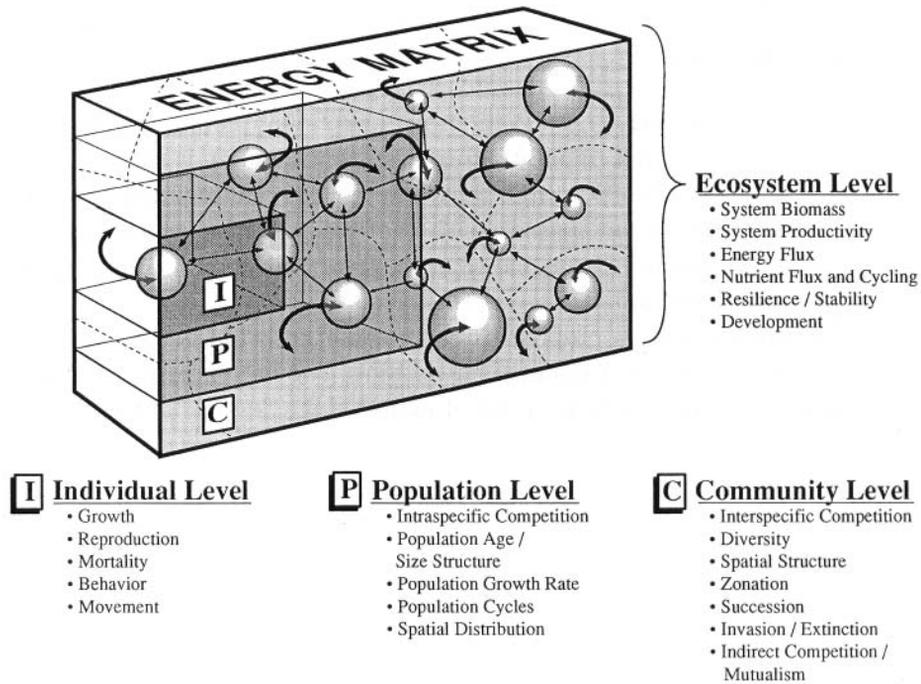


Fig. 3. Diagrammatic conceptualization of patterns and activities at different levels of complexity. Each sphere represents an individual abiotic or biotic entity. Abiotic is defined as nonliving matter. Broad, double-headed arrows indicate feedback between entities and the energy matrix for the system. The thin arrows represent direct interactions between individual entities. Much of ecology is devoted to studying interactions between biotic and abiotic entities with a focus on the effects of such interactions on individuals (I), populations (P) or communities (C) of organisms. Ecosystem ecology studies these interactions from the viewpoint of their effect on *both* the biotic and abiotic entities and within the context of the system. The boundaries of the system must be established to conduct quantitative studies of flux (see text).

(From Huston et al. 1988; modified)

factors (e.g. fluxes of nitrogen) within a landscape of “plants”. In fact, what is needed for synthesis and integration is the interplay between ecosystem flux and biotic competition for nitrogen. The schisms are seen most clearly in the rivalry, and at times disdain, between population ecologists and ecosystem ecologists. In an attempt to bridge the spectrum of ecological approaches (Figs. 1 and 2) and to promote synthesis and integration, the scientific staff of the Institute of Ecosystem Studies (New York) has proposed a new overarching definition of ecology:

Ecology is the scientific study of the processes influencing the distribution and abundance of organisms, the interactions among organisms, and the interactions between organisms and the transformation and flux of energy and matter.

Thus, ecology is the study of relationships among ecological entities, e.g. individual organisms, populations, and systems, and their environments (Fig. 3). This new definition highlights interactions and connotes experimentation, integration and synthesis. The definition describes a robust and dynamic field of inquiry, a unified science dedicated to understanding the ecology of the biosphere.

This definition also is proposed in an attempt to bring the subfields of ecology back together as a scientific discipline. The hallmark of ecology is its encompassing and synthetic view of nature, not a fragmented view.

An Ecosystem Approach

Tansley (1935) introduced the term “ecosystem”, and stressed the interaction between its living and nonliving components. An analysis of ecosystems represents one approach to the study of ecology, and it is one that I pursue.

Conceptually, the entire planet Earth, a lake or a single rock in the desert may be studied from an ecosystem point of view (see Gilmanov 1992 for discussion of the spatial dimensions of an ecosystem). The ecosystem provides a conceptual framework for the study of the interactions among individuals, populations, communities and their abiotic environments, and for the study of the change in these relationships with time.

An ecosystem is defined as a spatially explicit unit of the Earth that includes all of the organisms, along with all components of the abiotic environment within its boundaries; “. . . it is (these) systems . . . which . . . are the basic units of nature . . .” (Tansley 1935). Nevertheless, it is difficult to identify ecosystem units quantitatively because populations of organisms can vary individualistically in space and time (*sensu* Whittaker 1951). Furthermore, environmental factors, e.g. elevation, aspect, soil chemistry, also may vary continuously (e.g. Likens and Bormann 1985). Thus, the boundaries of an ecosystem must be explicitly defined for quantitative determination of, for example, flux of energy or mass balance determinations.

Ecosystem boundaries are usually determined for the convenience of the investigator rather than on the basis of some known functional discontinuity with an adjacent ecosystem. This artificiality occurs because the actual functional relationships between ecosystems usually are unknown. Nevertheless, arbitrarily determined boundaries may or may not represent a serious analytical problem depending on the system and on the objectives of the study (see Bormann and Likens 1967, 1979, Likens and Bormann 1972, Wiens et al. 1985). The problem of determining boundaries for ecosystems is more obvious in terrestrial environments than it is in many aquatic systems where, for example, the lateral boundaries for a lake are ostensibly apparent. Ideally, boundaries should represent the plane (boundary) at which short-term exchanges of matter (e.g. chemicals) are irreversible relative to the functional ecosystem, i.e. where cycling becomes a flux (see Likens 1975, and Likens and Bormann 1985). Thus, apparent boundaries, such as

the shoreline of a lake or river, may not be functional boundaries (see Likens 1984; and p. 63 ff.).

Because the structure and function of ecosystems change with time, ecosystems have a history of biotic-abiotic interactions. Ecosystem development is the change in structure and function of abiotic and biotic components that occurs with time (Bormann and Likens 1979). Successional changes in vegetational communities are one aspect of ecosystem development; soil formation is another. It is of utmost importance for quantitative, and particularly for comparative studies, to identify the current developmental stage of an ecosystem and how it has changed with time (see p. 19 ff.).

Different approaches have been used to study ecosystem-level questions and include: an empirical or natural history approach, a balance or budgetary approach, an experimental approach, a comparative approach and a modeling or simulation approach. These various approaches to the study of ecosystems will be discussed on pp.19 to 25).

From Organisms to Ecosystems

In the United States, the ecosystem concept is usually equated with energy flow and nutrient cycling. Obviously, much more is involved in the ecosystem approach. For example, the role of individual biotic and abiotic entities is important to ecosystem structure and may be critically important to ecosystem function (Fig. 3). Thus there are more than 850 species of organisms (Table 1) and more than 15 major (ecologically relevant) dissolved “species” of chemicals (cations and anions) in Mirror Lake, New Hampshire, USA (Fig. 4). Each of these entities presumably plays an important ecological role within the Mirror Lake ecosystem. But what if one of the abiotic or biotic entities were to increase in abundance or to disappear? What would be the effect on ecosystem function? Are the presence and activity of individual biotic species “key” to ecosystem-level processes, such as nutrient cycling? The effects of changes in biotic structure are relatively well studied at the population level in ecology, but poorly known at the ecosys-

Table 1. Estimated number of species in Mirror Lake, New Hampshire, USA

Type	Number of species ^a
Pelagic algae (phytoplankton)	138
Benthic algae	> 50 ?
Macrophytes	37
Pelagic bacteria	> 50 ??
Pelagic fungi	> 10 ???
Benthic bacteria	> 100 ??
Benthic fungi	> 10 ???
Pelagic zooplankton (includes Protozoa)	> 50 ?
Benthic invertebrates	> 400 ?
Fish	6
Reptiles and amphibians	4-7
Birds	4-5
Mammals	2-5
Total	> 850

^a ? indicates relative uncertainty

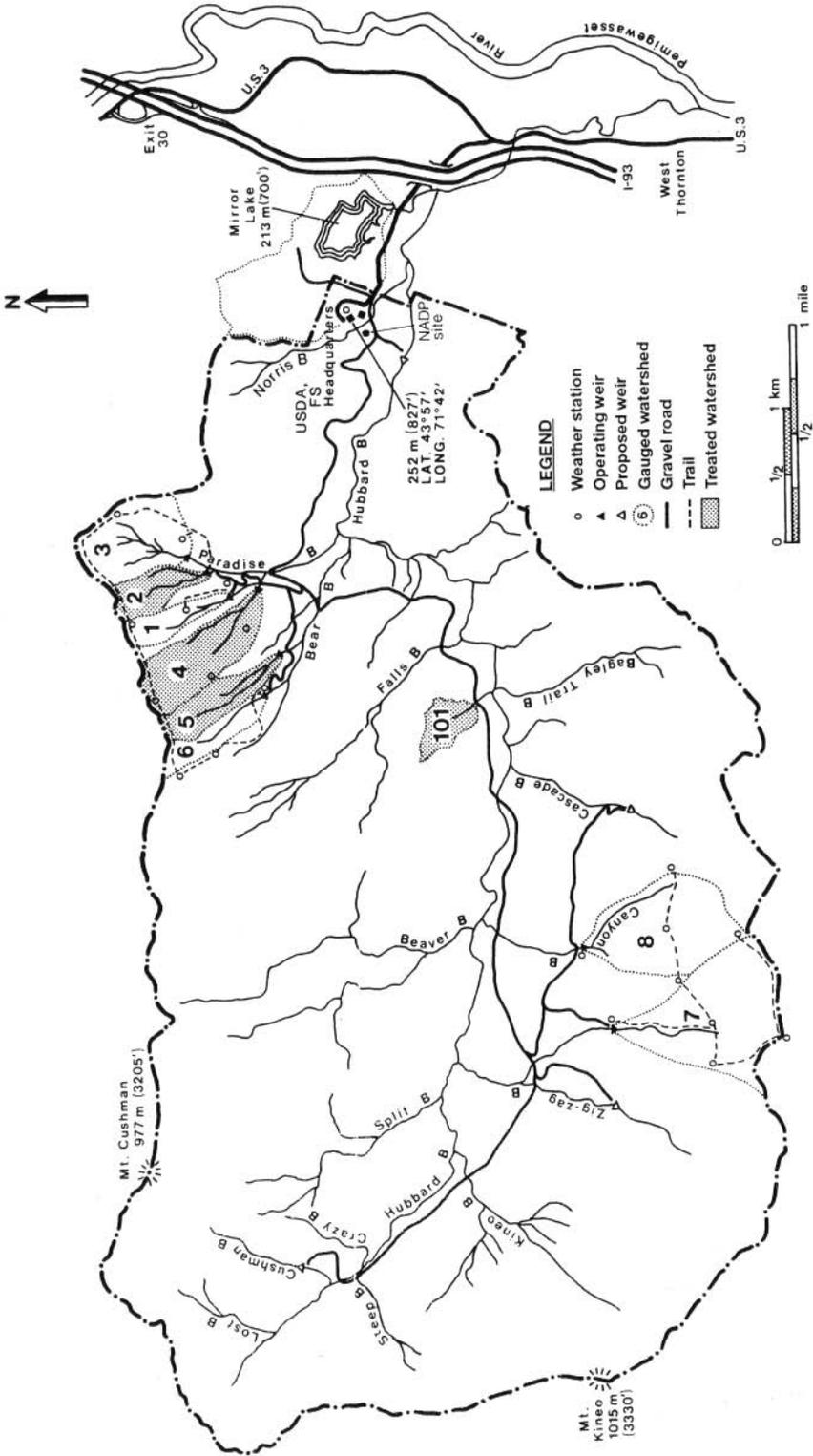


Fig. 4. Hubbard Brook Experimental Forest, West Thornton, New Hampshire, USA

tem level, whereas the importance of changes in abiotic structure are rather equally well known at both population and ecosystem levels of ecology (e.g. effect of a limiting nutrient). Andrewartha and Birch (1954) were early population biologists who emphasized the importance of abiotic factors in what they considered to be the basic problem in ecology – why is what where?

The examples of the role of an individual biotic species in ecosystem function, however, are relatively few. For example, Basnet et al. (1992) have shown the importance of Tabonuco trees (*Dacryodes excelsa* Vahl) in maintaining hillslope stability in the tropical rainforests of Puerto Rico. This species is common on ridgetops and on steep slopes. Because of an intraspecific habit of root grafting and of root anchorage to subterranean rocks and boulders this species was uniquely able to resist extreme winds (hurricane force) and heavy rainfall, and thus maintained vegetative cover over soils and reduced erosion on steep hillslopes during Hurricane Hugo in September 1989 (Basnet et al. 1992). Tabonuco was the most resistant forest tree species to damage from the hurricane in this area of the tropical forest.

In a very different way, three snail species (*Euchondrus albulus* Mousson, *E. desertorum* Roch, *E. ramonensis* Granot) have major effects on ecosystem processes in the Negev Desert in Israel (Shachak et al. 1987, Jones and Shachak 1990). By eating endolithic lichens, which grow inside the surface layers of rocks in the desert, these snails greatly accelerate the weathering rate of the rocks, as well as transfer of inorganic nitrogen, taken up by the endolithic lichens, to the soil. Thus, these species are important in accelerating weathering, in soil formation, and nutrient cycling processes of this desert ecosystem (Shachak et al. 1992).

Another example is Vitousek's (1990) finding that *Myrica faya*, an exotic nitrogen-fixing plant introduced into Hawaii in the late 1800's, altered the ecosystem processes of recent volcanic sites by fixing relatively large amounts of atmospheric nitrogen. Apparently, N-fixing plants were not present on such sites prior to this invasion.

Dale et al. (1990) reported that an outbreak of hickory bark beetles *Scolytus quadrispinosus*, which killed more than half of the hickory trees (*Carya glabra*, *C. cordiformis*, *C. ovata*, *C. tomentosa*) on the Walker Branch watershed in Tennessee, USA, caused a large change in calcium cycling within the ecosystem. Calcium concentrations in the tissues of hickory trees were higher than for any other tree species on the Walker Branch watershed (Johnson et al. 1990). Swank et al. (1981) found that defoliation of selected hardwood tree species by the fall cankerworm *Alsophila*

pometaria Harris increased the nutrient output of nitrogen in stream water from a forested ecosystem at the Coweeta Hydrologic Laboratory in North Carolina, USA. Rooting by wild pigs *Sus scrofa* in the Great Smoky Mountains National Park affected nutrient cycling, disturbed soil profiles, and reduced vegetative ground cover, leaf litter and populations of voles and shrews (Singer et al. 1984). Others (e.g. Hrbáček et al. 1961, Paine 1966, Dayton et al. 1984, Carpenter et al. 1985, Vitousek 1986) have suggested that species changes at the top of a trophic pyramid or physical disturbance caused by invading animals and plants have ecosystem-level effects.

In my view, there is a strong, underlying conceptual linkage between population ecology and ecosystem ecology, but it is poorly developed, little utilized and rarely documented. This linkage will be the subject of the next Cary Conference (1993) at the Institute of Ecosystem Studies.

What is the nature and value of structural or functional redundancy in an ecosystem? What is the role of an “important” species in the structure and function of ecosystems? To address such questions, we are planning to experimentally eliminate a major tree species from a New Hampshire forest ecosystem. Effects triggered by the selective removal of a tree species, often from indirect anthropogenic activity, on the ecological organization and function of ecosystems is poorly known (e.g. Pickett et al. 1992), yet this is an issue of obvious ecological importance, particularly since such biotic changes are a likely response to change in global climate (e.g. Davis 1990, Davis and Zabinski 1992).

The Hubbard Brook Ecosystem Study

Because of my experience and familiarity, I will use here examples from the Hubbard Brook Ecosystem Study (HBES) to illustrate some aspects of the ecosystem approach (Bormann and Likens 1967, 1979, Likens et al. 1977, 1985a). The site for the HBES is the Hubbard Brook Experimental Forest (HBEF) within the large, bowl-shaped Hubbard Brook Valley, located in the White Mountain National Forest of north-central New Hampshire, USA (Fig. 4). The HBEF was established by the USDA Forest Service in 1955 as a major center for hydrologic research in New England. The Hubbard Brook Valley is a unit of the landscape, and its lateral boundaries are clear (Fig. 4). A small oligotrophic lake, Mirror Lake, also is located within the Hubbard Brook Valley which provides an opportunity to investigate diverse kinds of air-land-water interactions (Likens 1985a). The HBES was initiated in 1963 and its development was slow and deliberate. We had no precedents to follow since similar comprehensive ecological studies of natural ecosystems had not been done previously (see Preface in Likens et al. 1977 for further description of research philosophy and early history). Our ecological and biogeochemical studies at Hubbard Brook focused on six similar south-facing watersheds (Fig. 4) containing soils, vegetation and climate characteristic of northern hardwood forests in the northeastern U.S.

Individual watershed-ecosystem units (catchments in European terminology) were established and hydrologically gauged within the HBEF to help conceptualize ecosystem- (watershed-) scale questions, and to facilitate quantification of such functional components as water and nutrient flux and cycling throughout a forested landscape. In humid areas like the HBEF, the flux and cycling of chemicals are intimately linked to the hydrologic cycle. Horizontal ecosystem boundaries, therefore, are established in accordance with the phreatic divides of the watershed (catchment). Because deep seepage of water from these watershed-ecosystems at Hubbard Brook is negligible (Likens et al. 1977), it is possible to do quantitative mass-balance analyses. Simultaneous data from several, adjacent watersheds provide a reference for whole-system, experimental manipulations (e.g. Likens 1985c) and an opportunity to evaluate spatial variability. High spatial and temporal variability often characterize ecological relationships, e.g. soil structure and chemistry may be very heterogenous from meter to meter on a hillslope, but the ecosystem approach can help to integrate this variable information and,

thus, promote overall understanding at larger scales, e.g. watersheds. Early in this study, we developed a broad conceptual model (Bormann and Likens 1967), and then began to do ecosystem-level experiments (Likens 1985c).

The ecosystem approach also has been used at Hubbard Brook to evaluate complex functional processes of ecosystems, such as evapotranspiration and chemical weathering (e.g. Likens et al. 1977). Recently the ecosystem approach has been used to estimate the dry deposition of sulfur from the atmosphere (Likens et al. 1990b; see pp. 42 to 45). Such components are among the most difficult to evaluate quantitatively for large-scale systems. Some examples of the application of the ecosystem approach at Hubbard Brook and elsewhere will be found in the following sections. Chapter II, Section 2 illustrates the value of sustained ecological research and Section 3 addresses linkages between air, land and water at the ecosystem scale of integration.

Concluding Remarks. *The ecosystem concept has great utility in addressing large-scale ecological questions. When A. G. Tansley introduced the ecosystem concept in 1935, he was attempting to correct the abuse of terms and concepts in vegetation science. Now, however, although the term, ecosystem, has gained widespread acceptance, its popular usage and application frequently abuse the concept that Tansley intended and that is understood by practicing ecosystem scientists. As described above, the term, ecology, is similarly abused in popular useage. In the following sections I will provide some examples of the use and abuse of ecology, and in particular, ecosystem science, in addressing questions and problems that are important to the ecological relationships of organisms, including humans. I also will review briefly the relation of ecosystem science to resource management, political decision making and ethics. The contrasts between the approach of professional ecological science and environmentalism are addressed on pp. 138 and 142.*

II

STYLE AND METHOD IN ECOSYSTEM ECOLOGY

(1) Approaches to the Study of Ecosystem Ecology

“Some circumstantial evidence is very strong, as when you find a trout in the milk.”

Henry David Thoreau
[*Journal*, 1854]

The goal of ecosystem science is to integrate information from studies of the interactions between individuals, populations, communities and their abiotic environments, including the changes in these relationships with time. Amid this complexity, several approaches have been used in attempts to synthesize understanding at the ecosystem level. These approaches include (1) empirical or natural history studies, (2) balance or budgetary studies, (3) experimental studies, (4) comparative studies, and (5) modeling or computer simulation studies. Each of these approaches has been used effectively, and each has its own merits and defects. I will review briefly here the major aspects of each of these approaches.

An Empirical or Natural History Approach

According to Webster’s Third New International Dictionary (1968) “natural history” is “a modern branch of inquiry usually restricted to a consideration of [natural objects] from an amateur or popular rather than a technical or professional point of view.” Natural history is demeaned frequently by scientists and de facto relegated to amateurs and so-called “ecofreaks”. Nevertheless, it can be argued that observing and describing facts about “nature” and gaining experience with these facts is serious, scientific inquiry, and the critical first step in the formulation of meaningful questions and testable scientific hypotheses, and development of theory (e.g. Likens 1983, G. E. Hutchinson, pers. comm. 1985). The efforts of Charles Darwin probably provide the most exemplary case in this regard. Long-term observations, especially (see Section 2), can be crucial for establishing patterns, and for illuminating relationships. Such long-term data sets usually are more useful and productive relative to generating ecological understanding

when they are question driven. Thus, successful attempts to study the complexity and diversity of natural ecosystems (Sections 2 and 3) usually require a firm foundation of empirical, descriptive study of the natural history of ecosystems. A better, modern working definition of natural history may be provided by a definition of the root words: *natural* – “relating to, or concerned with nature as an object of study and research”, and *history* – “a systematic written account comprising a chronological record of events and usually including a philosophical explanation of the cause and origin of such events.”

An ecosystem ecologist would attempt to assemble empirically generated bits of data into a more comprehensive understanding about the structure, function and development of an entire ecosystem, e.g. a lake. Most people would consider lakes to be “attractive” because of their aesthetic qualities and because of their interesting and varied natural history; scientifically, lakes are intriguing and appealing because they appear to be clear units of nature (*sensu* Tansley 1935) with boundaries. Bounded “units” attract attention within the mosaic of natural complexity, and conceptually are more tractable for study. Much of the history of the discipline of limnology is characterized by attempts to integrate empirical data obtained from physical, chemical, biological, hydrological and geological perspectives into an understanding of the structure, function and development of inland, surface waters (e.g. Hutchinson 1957, 1967, 1975, Ruttner 1963, Wetzel 1983, Likens 1985c). As such, limnology may be one of the few truly integrative disciplines, and has its roots, as does most of ecology, in natural history.

A Balance or Budgetary Approach

Studies of energy budgets and balances of mass provide a quantitative means of answering ecosystem-level questions about rate and control of flux and cycling. Boundary considerations can be a problem in this approach, but may be addressed in various ways (pp. 9 to 10; Bormann and Likens 1979). Balance studies often treat the ecosystem as a “black box”, but also provide an efficient means to identify fundamental processes within the black box. Balance approaches have been used to estimate difficult-to-measure fluxes, such as dry deposition from the atmosphere or weathering release of chemicals. Frequently, such estimates are criticized because the unknown component may have a small value and is calculated as the

difference between two large values. In such cases, great effort must be expended to quantify uncertainties. Mass balances represent one way to integrate diverse information from large areas, and are useful in providing quantitative information that is important in management decisions pertaining to disturbance of ecosystems, for example, inputs of pollutants and land-use changes. Mass balance values can be compared readily over different spatial and temporal scales. Examples of the mass-balance approach are given in Section 2.

An Experimental Approach

Experimental manipulation of structural and/or functional components of entire ecosystems is a powerful analytical way to study large systems (e.g. Schindler 1973, Likens 1985c, Schindler et al. 1985, Tilman 1989, Franklin et al. 1990). Such studies provide an obvious means to test hypotheses, and results frequently illuminate fundamental mechanisms at the ecosystem level. Major examples of experimentation at the ecosystem level include studies of the role of water clarity in lake ecosystems (Peter and Paul Lakes, Michigan, USA: e.g. Johnson and Hasler 1954, Stross and Hasler 1960), studies of the relative role of nitrogen and phosphorus in the eutrophication of lakes, and studies of the acidification of lakes (Experimental Lakes Area studies, Ontario, Canada: e.g. Schindler 1973, 1980, 1988b, Schindler et al. 1985), studies of the effects of deforestation on water yield and biogeochemical response in catchments (Coweeta Hydrologic Laboratory, North Carolina, USA: e.g. Swank and Crossley 1988; Hubbard Brook Ecosystem Study: e.g. Likens et al. 1970, Bormann and Likens 1979), studies of trophic interactions in lakes (e.g. Carpenter et al. 1985), studies of the acidification of terrestrial ecosystems (the Reversing Acidification in Norway [RAIN] Project: e.g. Wright et al. 1988), and studies of the effects of within-stream processes on catchment mass-balances (Section 3).

Experimental manipulations of entire ecosystems often are very expensive in terms of human effort and financial cost. Also it is critical to have a reference system against which experimental results can be compared. A reference system is particularly valuable for assessing natural, temporal variability during long-term experiments. Strict control systems are difficult, if not impossible, to establish because of the inherent complexity and variability of natural ecosystems (Likens 1985c). Thus, statistical problems of pseudoreplication may be severe for ecosystem-level experiments (Hurl-

bert 1984). Nevertheless, in my opinion, carefully designed experimental manipulation is the most powerful, scientific approach for studying process-level questions relative to ecosystems.

A Comparative Approach

Comparative studies of diverse ecosystems (also called cross-system studies) are an attempt to elucidate fundamental processes, and currently are becoming more common (Cole et al. 1991). Structural and/or functional components, such as species composition or nitrification rate, may be compared among systems, often utilizing existing, in-depth information from individual ecosystem studies, or results from specially designed studies (experiments) of selected systems. Cross-system studies of mass balances among diverse ecosystems frequently are quite informative relative to both scientific understanding and management considerations. Results provided by cross-system studies may be more revealing relative to *general* ecosystem processes, at least from a research efficiency point of view, than those from detailed studies of an individual ecosystem (e.g. Caraco et al. 1991). On the other hand, in-depth and sustained studies at individual sites not only provide the data to be compared, but also the perspective about the status of ecosystem development for the site.

Considerations of history and developmental stage of ecosystems being compared are critical to success. For example, age, time since last major disturbance, types of disturbance, and nutritional state are critical types of information that are needed to compare the structure and function of diverse ecosystems. Without such information the results of comparisons may be totally misleading. For example, to make this apples-and-oranges type of comparison with an excessive example, comparing the calcium in a pre-ossified leg of an elephant with that of the leg of a 60-yr-old human could lead to serious ambiguity (also see Kinne 1980, regarding the comparative ecology of disease in marine ecosystems). Sometimes these comparisons can be misleading or go awry even when attempts are made to be thoughtful, e.g. comparison of the nitrate concentrations among dimictic lakes only during overturn periods, but ignoring the developmental state of the watershed or prior use of agricultural fertilizer in the watershed. Obviously, other factors that differ among sites, for example climate, can contribute to variability in comparative studies, but these are obvious factors to consider, whereas historical and developmental considerations often are not.

Because ecosystems are open systems with regard to fluxes of energy and matter, a knowledge of context and surrounding matrix also is critical for evaluating comparisons among ecosystems. Aspects of contextual relationships are components of landscape ecology (e.g. Forman and Godron 1986, Urban et al. 1987, Turner 1990).

Some recommendations to guide comparative ecological studies are given in Peters et al. (1991). They stress the importance of clarifying goals and limitations in pursuing this approach, as is the case with each of the approaches.

A Modeling or Computer Simulation Approach

Conceptual modeling and computer modeling and simulation have been important tools for studying the complexity of ecosystems (e.g. Hall and Day 1977, Cosby et al. 1985, Horn et al. 1989, Shugart 1989, Costanza et al. 1990, Turner and Gardner 1991). Models may be a useful research tool in attempts to evaluate process formulations and to integrate process-level studies within an ecosystem framework. They also may be useful as a predictive tool for resource managers and decision makers in attempts to evaluate the effects of pollution or disturbance, as well as alternative management strategies, in large, complex systems (Driscoll et al. 1992). To be useful to ecosystem studies, models must be designed in accordance with the range of spatial and temporal scales of the research questions being addressed (Fig. 5).

Using the JABOWA Forest Growth simulation model, a biomass accumulation model and components of the shifting-mosaic steady-state model were developed for the Hubbard Brook Experimental Forest (HBEF) (Bormann and Likens 1979). These models allowed us to formulate and test hypotheses about the long-term structure, function and development of the Hubbard Brook ecosystem that would not have been possible otherwise. Models are limited by data and understanding so they must be continually upgraded. For example, the potential development and timing of pest outbreaks is not considered in JABOWA, but in fact these outbreaks had major effects on the long-term biomass accumulation model for the HBEF (Christ et al. 1992).

Although the debate continues as to whether models should be simple or complex to be most effective, it is clear that simplicity has many advantages (e.g. Roughgarden et al. 1989) and that models must be tied regularly to reality by calibration with ground-truth measurements.

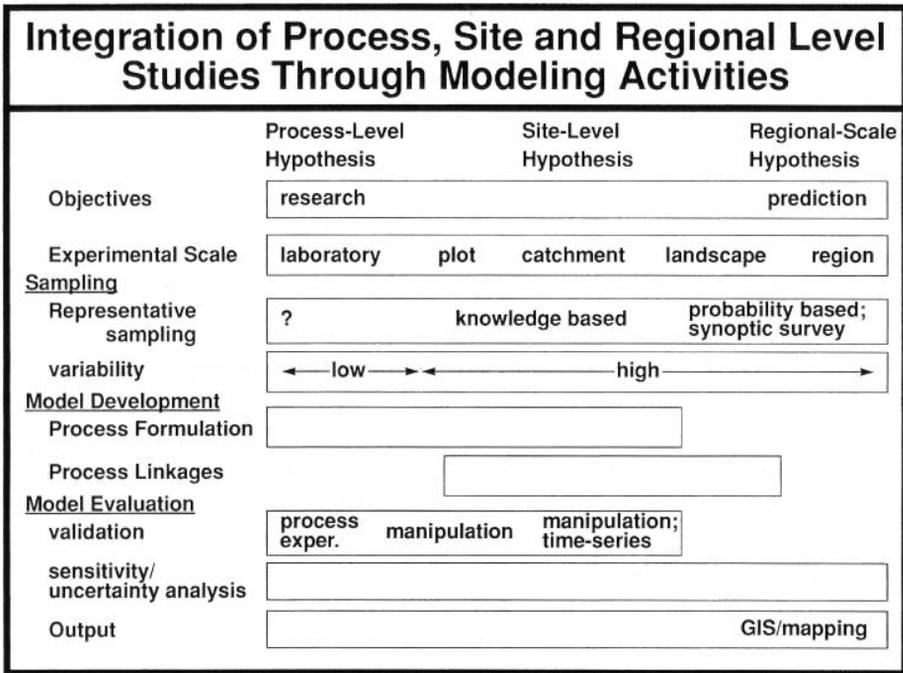


Fig. 5. A diagrammatic scheme for the application of research-orientated and predictive-orientated modeling activities for addressing questions at different scales of complexity. As questions concerning ecosystem structure, function and development shift from being research-orientated to more predictive, it is necessary to change the scope of study to larger spatial scales and longer temporal scales. Modeling strategies must be modified accordingly. A critical component of modeling activities at all scales is analysis of sensitivity, uncertainty and validation. GIS is geographic information system. (From Driscoll et al. 1992)

Concluding Remarks. *Studies of ecosystems should utilize all of the approaches described above in attempts to unravel complexity, develop ecological understanding and provide useful information for decision makers and managers. In all areas of ecology, and in science in general, the convergence and integration of information from different points of view, different disciplines and different approaches are what lead to major advances and breakthroughs in understanding. To gain comprehensive understanding about complex ecosystem function, including relationships among the integral components (e.g. Fig. 6), will require diverse talents and approaches.*

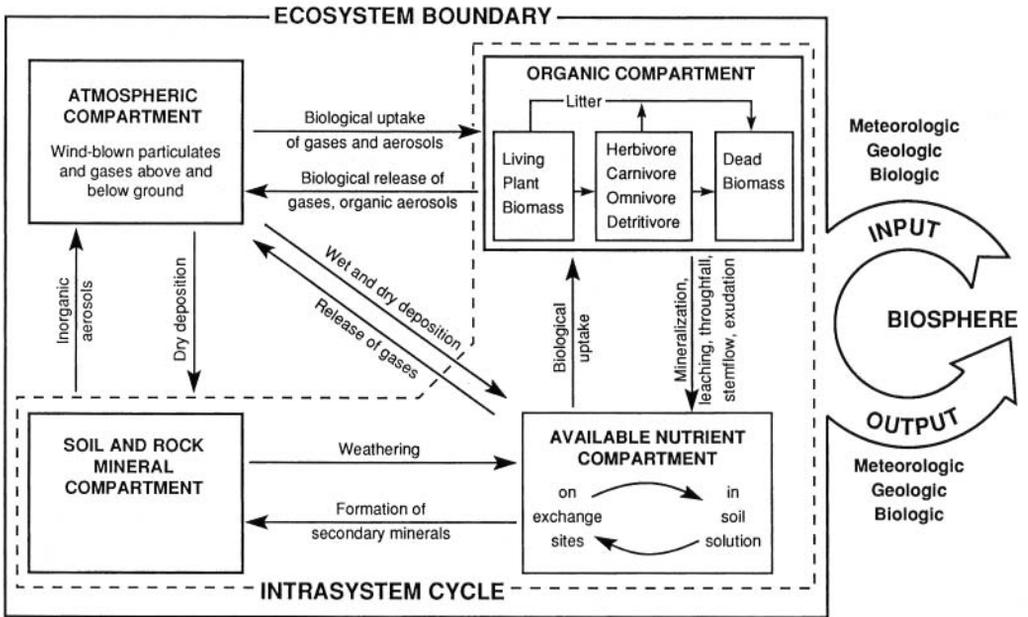


Fig. 6. Model depicting nutrient relationships in a terrestrial ecosystem. Inputs and outputs to the ecosystem are moved by meteorologic, geologic and biologic vectors (Bormann and Likens 1967, Likens and Bormann 1972). Major sites of accumulation and major exchange pathways within the ecosystem are shown. Nutrients that, because they have no prominent gaseous phase, continually cycle within the boundaries of the ecosystem between the available nutrient, organic matter and primary and secondary mineral components tend to form an intrasystem cycle. Fluxes across the boundaries of an ecosystem link individual ecosystems with the remainder of the biosphere. (From Likens et al. 1977; modified)

(2) Sustained Ecological Research

“This song of the waters is audible to every ear,
but there is other music in these hills,
by no means audible to all.
To hear even a few notes of it you must first
live here for a long time,
and you must know the speech of hills and rivers.”

Aldo Leopold
[*Song of the Gavilan* (1940)]

Sustained Ecological Research (SER) is research and monitoring done continuously over long periods (probably more than 5 yr) to study long-term ecological patterns and processes. One characteristic of such research is that its duration must be at least as long as the phenomenon being evaluated, or scaled to the frequency of the event being studied (Likens et al. 1977). Proper SER is not mindless collection and storage of data, but is a powerful tool to help focus research on fundamental questions. SER also has great potential for identifying and defining environmental problems, and is valuable to decision makers. At a recent international Cary Conference a statement in support of SER was agreed to by all of the participants at the Conference (Likens 1989a). SER was identified as “a critical need” in ecology (Table 2).

The Cary Conference statement proposed that understanding obtained from sustained ecological research can contribute significantly to the identification and resolution of complex environmental problems. To be useful in assessing and mitigating environmental problems, however, sustained ecological research must be designed and integrated as a partnership between scientists and resource managers (Table 2). In this partnership, scientists should provide managers or decision makers with the best information available including measures of uncertainty. Managers then should translate this information into action, but should understand fully that the management action may not be perfect and that it will change with time. Revised management procedures should be developed in accordance with new information obtained by *sustained* ecological research. One of the prime goals of this partnership between managers and scientists is to foster

Table 2. Sustained Ecological Research: a critical need. Statement adopted at the Cary Conference in Millbrook, New York, on 13 May 1987; revised 4 July 1987. Reprinted from Likens (1989a), page v

Ecological understanding is required to develop environmental policies and to manage resources for the benefit of humankind. Sustained ecological research is one of the essential approaches for developing this understanding and for predicting the effects of human activities on ecological processes. Sustained research is especially important for understanding ecological processes that vary over long periods of time. However, to fulfill its promise, sustained ecological research requires a new commitment on the part of both management agencies and research institutions. This new commitment should include longer funding cycles, new sources of funding, and increased emphasis and support from academic and research institutions.

Because they have common long-term goals, we propose a new partnership between scientists and resource managers. Elements of this partnership include:

- (1) Agreement by scientists to answer the questions put to them by managers, while making clear the level of uncertainty that exists and what additional research needs to be done.
- (2) Agreement by managers to give serious consideration to these answers and to support the continuing research toward better answers.

Sustained Ecological Research supported by this new partnership can contribute significantly to the resolution of critical environmental problems.

clear and honest communication between the partners, and meaningful communication with the public. Such an interactive partnership between ecologists and managers is woefully lacking today (see pp. 127 to 142), but is critical to sound management and conservation of natural resources.

Strayer et al. (1986) offer some guides for the successful execution of SER, based on a survey of about 100 ecologists engaged in such work. The primary ingredient seemed to be the long-term dedication of one or a few project leaders. Some of the other elements included frequently in the responses were simplicity of design, role of experimentation, protection and management of the site, management of personnel and data, importance of monitoring, role of synthesis, and serendipity. A successful mix of these ingredients obviously depends upon the people involved, historical timing and circumstances unique to the site or research goals. Fortunately, the awareness of the importance of SER for developing ecological under-

standing is growing (Likens 1983, 1989a, Callahan 1984, Wiens 1984, Schindler et al. 1985, Strayer et al. 1986, Franklin 1988, 1989, Elliott 1990, Franklin et al. 1990, Magnuson 1990, Risser 1991).

It is apparent from geologic records, and from paleoecological records provided by lake and wetland sediments that ecosystems change with time (e.g. Davis et al. 1985). Changes in structure and function of ecosystems with time have been called ecosystem development (Bormann and Likens 1979), and are a critical component for understanding natural systems, as well as justification of the need for sustained ecological research (see also pp. 9 to 10 and pp. 19 to 25). Because ecosystems change with time, management plans and policies also must change with time. Static preservationist policies rapidly become outdated or irrelevant for most dynamic ecosystems that are changing because of both natural and anthropogenic influences. Indeed a new paradigm in ecology points out that natural ecosystems are neither closed nor self regulating (the balance of nature concept), but instead stresses a "flux of nature" concept, which provides a more realistic basis for understanding and conservation of dynamic, living ecosystems (e.g. Pickett et al. 1992). It is interesting to note that this "new" paradigm was foreshadowed more than 50 years ago in the writings of Aldo Leopold (1939).

There are many examples of important ecological insights that have been produced by SER in combination with the ecosystem approach (e.g. see Schindler 1977, 1988b, Jónasson 1979, Ulrich et al. 1979, 1980, Waring and Franklin 1979, Lawes Agricultural Trust 1984, Brock 1985, Swank and Crossley 1988, Wright et al. 1988, Johnson and Van Hook 1989). I have selected a few examples here and will draw heavily on the results from the Hubbard Brook Ecosystem Study.

Examples from Ecosystem Science

The Hubbard Brook Ecosystem Study

My colleagues and I have done sustained ecological research at the Hubbard Brook Experimental Forest (HBEF) in the White Mountains of New Hampshire for more than 28 years (see pp. 15 to 16). For example, Hubbard Brook is the site of the longest, continuous record of precipitation chemistry in North America. This long-term research, coupled with experimental work particularly at the level of an entire ecosystem, has led

to several new insights relative to understanding and management of the northern hardwood forest ecosystem, as well as to some environmental problems such as acid rain. SER at Hubbard Brook led to the discovery of acid rain in North America (see pp. 107 to 109).

Water. A major objective of the HBES is the quantitative measurement of the flux and cycling of water and chemicals through forest and associated aquatic ecosystems. To make quantitative measurements, precipitation collectors have been established at high density in cleared areas throughout the HBEF (Fig. 4). A gauging weir is attached to the bedrock at the base of each watershed-ecosystem so that all liquid water will be forced to pass through it for accurate measurement. Deep seepage is negligible in these watershed-ecosystems (Likens et al. 1977). Thus, it has been possible to make continuous, quantitative measurements of the flux of water at Hubbard Brook since 1956 (Likens et al. 1985a, Federer et al. 1990). The water-year (1 June–31 May) is used to determine annual balances at Hubbard Brook because it is assumed that the change in water storage in the soil of the ecosystem is minimal from one June 1st to the next (Federer et al. 1990).

Measurements were begun in 1963 in Watershed No. 6 (W6 is 13.2 ha in size); they provide the longest, continuous record of precipitation and streamwater chemistry for the HBES. Thus, W6 is used as the biogeochemical reference, watershed-ecosystem for the HBES. Adjacent watershed-ecosystems (Fig. 4) are available for experimental manipulation and provide insights about spatial variability within the landscape.

The long-term record of hydrologic flux at Hubbard Brook (Fig. 7) provides numerous insights about the function of forested landscapes. Large (order of magnitude), temporal fluctuations are apparent (e.g. Fig. 8) from these hydrologic data (see also Likens et al. 1985a, Federer et al. 1990), but spatial differences in hydrologic flux are relatively small among watersheds. An example of the spatial variability in precipitation, streamflow and evapotranspiration among four, south-facing experimental watersheds is given in Table 3.

On average it rains about every third day, and about 30% of the annual precipitation falls as snow at Hubbard Brook (Likens et al. 1985a). The long-term (1963–1990) average precipitation amount for W6 is about 139.3 ($s_{\bar{x}} = 36.9$) cm yr⁻¹. The amount of precipitation for W6 during water-year 1964–65 was the driest on record (98 cm) and during 1973–74 was the wettest (189 cm), a 1.9-fold difference (Fig. 7). The return intervals for these extreme years cannot be calculated precisely, but may be

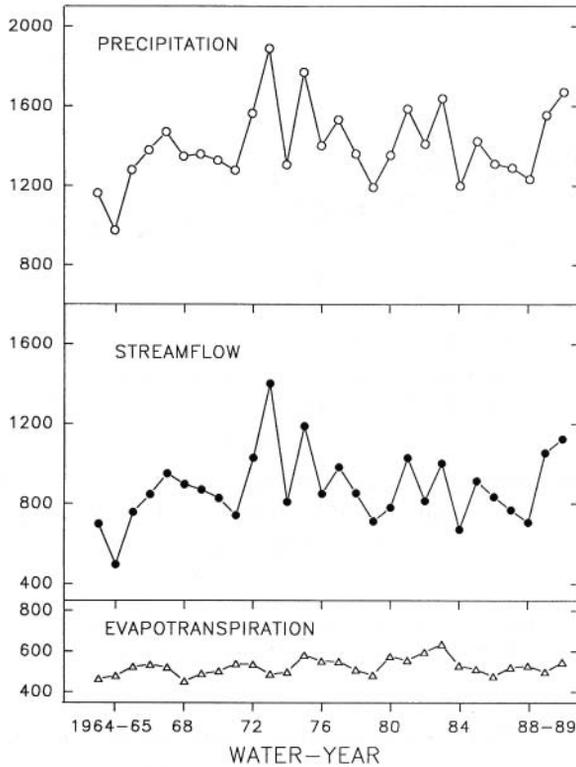


Fig. 7. Annual precipitation, streamflow and evapotranspiration for forested Watershed 6 of the Hubbard Brook Experimental Forest during 1963–64 through 1990–91. Annual evapotranspiration is calculated as the difference between annual precipitation and annual streamflow. Each water-year extends from 1 June to 31 May

100 years or more. Annual precipitation (97.3 cm) during calendar-year 1961 for W3, which has a longer hydrologic record than W6 at Hubbard Brook, was the driest calendar-year on record, whereas the water-year of 1964–65 was the driest (93.8 cm) for W3 (Federer et al. 1990). These differences show the problems that may be encountered from the way long-term data are aggregated temporally (Likens et al. 1990a).

No statistically significant long-term, temporal trend in amount of annual precipitation, streamflow or evapotranspiration was found for the period 1963–1991 at the HBEF (Fig. 7). Annual precipitation and streamflow amount increased significantly from 1963–64 to 1973–74, but these trends were determined largely by the two dry years in 1963–64 and 1964–65, and the two wet years in 1972–73 and 1973–74. There was no

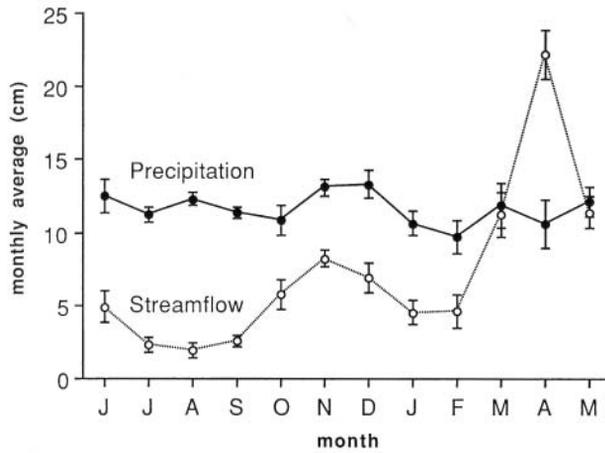


Fig. 8. Average monthly precipitation and streamflow for Watershed 6 of the Hubbard Brook Experimental Forest during 1964–1988. Error bars show one standard deviation of the mean

Table 3. Annual hydrologic budget for four watershed-ecosystems of the Hubbard Brook Experimental Forest during 1979–80*. (From Likens et al. 1985a; modified)

Watershed-ecosystem	Area (ha)	Precipitation (cm)	Streamflow (cm)	Evapotranspiration** (cm)
W1	11.8	113.7	71.4	42.4
W3	42.4	113.9	69.3	44.6
W5	21.9	115.5	70.2	45.3
W6	13.2	119.3	70.8	48.5
Mean		115.63	70.41	45.21
Standard error of the mean		1.30	0.45	1.27
% of the total		100	61	39

* Estimates for annual evapotranspiration do not consider differences in soil water storage from year to year. Estimates of such storage differences between years, based on the BROOK model (Federer and Lash 1978), rarely exceed 4 cm and commonly are less than 1 cm. Neglecting changes in soil-water storage could lead to errors of up to 7 % in estimating annual evapotranspiration

** Precipitation minus streamflow

apparent long-term trend in these data after 1973–74. An intriguing and unexplained 6-year cycle is suggested by the long-term data for annual evapotranspiration (Fig. 7).

Monthly precipitation at Hubbard Brook is rather constant in amount; for W6 it averages 11.6 cm mo^{-1} ($s_{\bar{x}} = 0.32$). In sharp contrast, 52% of the annual streamflow occurs during March, April and May when the snowpack is melting, and 8% occurs during July, August and September (Fig. 8). Individual months may differ significantly from these average values. For example, five months during 1964–65 (June, September and October of 1964, and March and May of 1965) had precipitation amounts that were 50% or less of the respective long-term monthly averages for W6 (Fig. 8, Federer et al. 1990). In fact, values for March and May 1965 were the lowest ever recorded for W6 (Federer et al. 1990). Such extreme temporal events are useful, however, in clarifying relations that are dependent on hydrologic fluctuations.

One insight gained from long records of the hydrologic cycle at Hubbard Brook is that the amount of water draining from forest ecosystems within the HBEF is related directly to the amount of water input in rain and snow each year; and it is essentially a 1:1 relationship with an r^2 of 0.95 (Fig. 9). Because there is negligible deep seepage from these watershed-ecosystems, evapotranspiration amount can be estimated as the difference between precipitation and streamflow. The long-term (1963–1990) average streamflow for W6 is $86.9 (s_{\bar{x}} = 3.4) \text{ cm yr}^{-1}$. Thus, the long-term, average evapotranspiration is 52.4 cm yr^{-1} , or 38% of the annual precipitation input.

Based on long-term data, annual evapotranspiration was related directly to annual precipitation but the statistically significant slope is 0.09 and the regression explains only 17% of the variability. Indeed, the annual amount of evapotranspiration for this forested landscape was relatively constant from year to year even though annual precipitation varied by about two-fold. During the wettest year, evapotranspiration accounted for 26% of the annual precipitation amount and 35% of the annual streamflow amount, whereas during the driest year these percentages were 49 and 97, respectively (Fig. 9). Transpiration losses were estimated at about 75% of the total evapotranspiration water lost each year (Likens et al. 1970). Apparently, the vegetation exacts its toll on the water balance first and whatever is left over then drains out of the system, and plants appear to use about the same amount whether it is a wet or dry year. These relationships were unanticipated prior to these long-term data, which provided new insights about the functioning of the ecosystem.

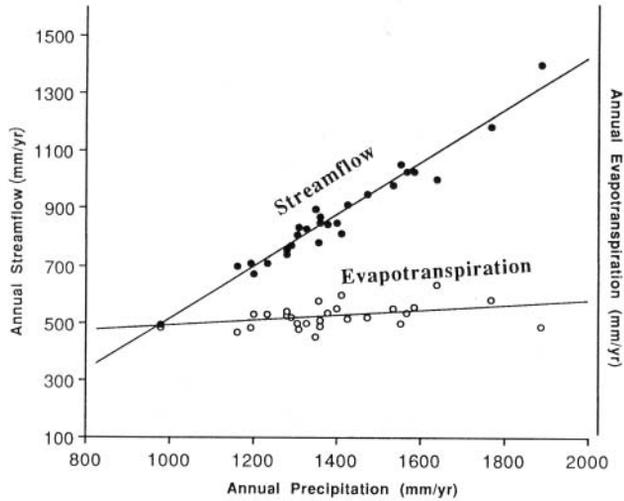


Fig. 9. Relationship among precipitation, streamflow, and evapotranspiration for Watershed 6 of the Hubbard Brook Experimental Forest from 1963–64 to 1989–90. Regression lines fitted to these data are $Y = b + aX$; where Y = annual, water-year streamflow or evapotranspiration in mm yr^{-1} ; b = Y intercept; a = slope; X = annual, water-year precipitation expressed in mm yr^{-1} . Regression line for streamflow has a probability of a larger F -ratio < 0.001 and an r^2 of 0.95; evapotranspiration has a probability of a larger F -ratio of < 0.03 and an r^2 of 0.17

Short-term fluctuations in streamflow during an annual cycle can be very important to the overall biogeochemical flux of water, dissolved substances, and particulate materials. Occasional peaks in discharge resulting from storms may result in outputs from the ecosystem that are far out of proportion to the duration of the event. For example, during one 50-month period at Hubbard Brook one streamflow event, ranging from 310 to 340 liters s^{-1} and comprising only 0.2% of the total streamflow and less than 1 h during the entire 50 months, exported 16% of the total eroded particulate matter for the period. During this same 50-month period, 77% of the stream water was discharged at rates between 0 and 30 liters s^{-1} and 14% of the total particulate matter was exported (Bormann and Likens 1979). Such patterns are well known from watershed studies, but cannot be evaluated properly for an individual site or landscape without sustained research.

Long-term records of precipitation chemistry provide additional insights. For example, annual, volume-weighted concentrations of hydrogen ion and sulfate have declined in precipitation since the beginning of our study (Fig. 10). Nitrate concentrations in precipitation increased during the initial years of the study (1964–1971), but then showed no long-term trend thereafter.

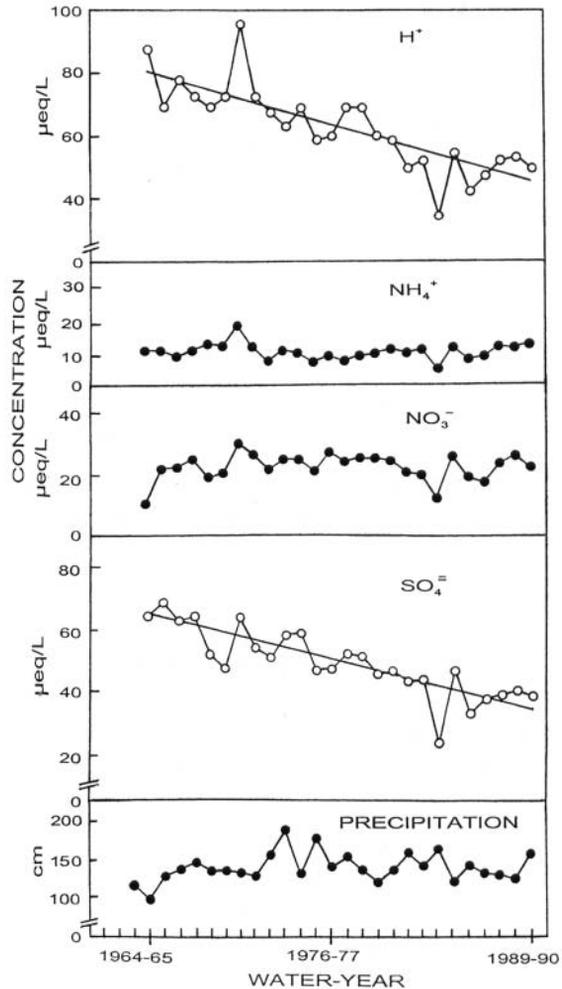


Fig. 10. Annual volume-weighted concentration of H^+ , NH_4^+ , NO_3^- and $SO_4^{=}$ in precipitation and amount of precipitation for Watershed 6 of the Hubbard Brook Experimental Forest. Regression lines have a probability for a larger F -value of <0.05

Short-term records, however, can be very misleading with regard to long-term trends. With hindsight, this is an obvious conclusion, but one, nevertheless, that frequently is ignored in describing patterns for natural systems. The long-term pattern for hydrogen ion at Hubbard Brook provides a clear example (Fig. 11). It required 18 years of continuous monitoring at the HBEF before a statistically significant ($p < 0.05$) regression line could be fitted to these long-term data (Fig. 12). Any one of the short-term records does not reflect accurately the long-term trend (Fig. 11), and for a politically charged environmental issue such as acid rain, the difference in interpretation between such long- and short-term patterns of hydrogen-ion

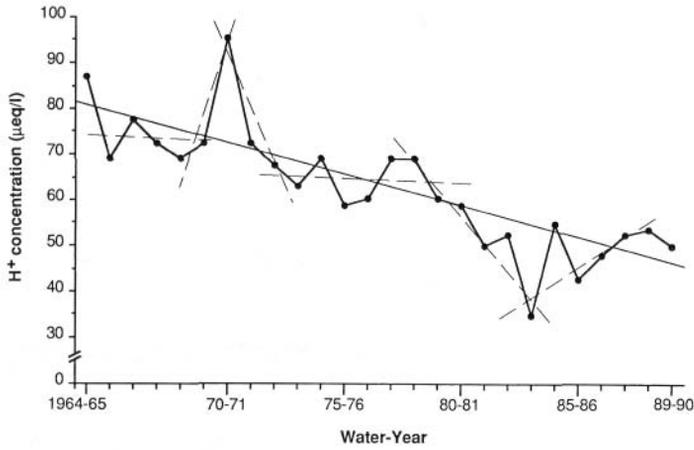


Fig. 11. Annual, volume-weighted concentration ($\mu\text{eq liter}^{-1}$) of hydrogen ion for Watershed 6 of the Hubbard Brook Experimental Forest from 1964–65 to 1989–90. The long-term regression line has a probability for a larger F -value of <0.05 ; $r^2 = 0.66$. Shorter, dashed lines are fitted by eye. (From Likens 1989b; modified)

concentration in precipitation is important for decision makers. Obviously, short-term (1 to 5 yr) data are useful, and they contribute to an overall understanding. The important managerial insights come from the perspective of the longer term, however, because the physical-chemical-biological

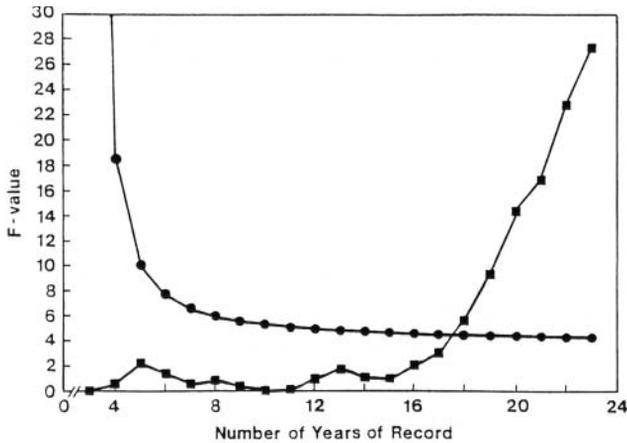


Fig. 12. Critical values of F -distribution (\bullet) for a linear regression at a probability of <0.05 and calculated F -values (\blacksquare) for an increasing record of actual data (1964–65 to 1986–87) for annual, volume-weighted hydrogen-ion concentrations in precipitation for Watershed 6 of the Hubbard Brook Experimental Forest. (From Likens 1989b)

factors may fluctuate dramatically from year to year or from decade to decade, and the overall trend may be difficult to discern without long-term data.

Important seasonal or monthly patterns are apparent in these long-term data as well (Fig. 13). Determining the ecological causes and role of these patterns is an ongoing effort in the HBES (e.g. Likens et al. 1990a).

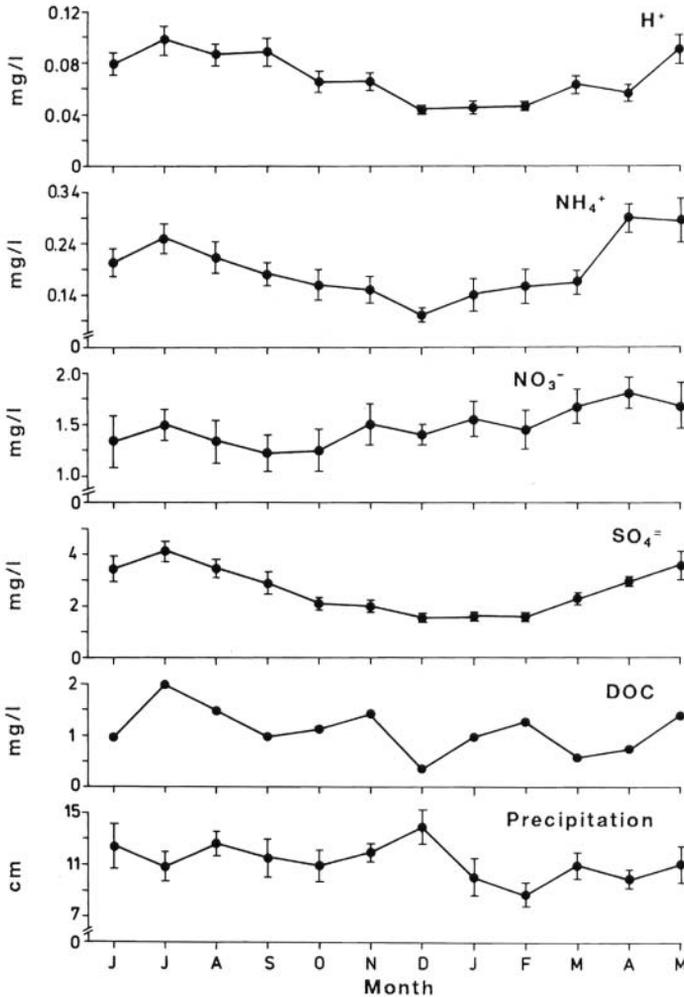


Fig. 13. Average monthly volume-weighted concentrations in bulk precipitation and amount of precipitation from 1964 to 1980 for the Hubbard Brook Experimental Forest. Average DOC (dissolved organic carbon) concentrations are for 1976–77 in samples collected near the US Forest Service Headquarters station. Vertical bars are \pm one standard deviation of the mean. (From Likens et al. 1985a)

Lead. The dispersal of toxic metals in the atmosphere, for example lead, from anthropogenic activities is an important environmental problem. It has been estimated that by 1980 over 300 times more lead was added to the global atmosphere each year by human activity than was added by natural activity (Table 4). Such atmospheric pollution clearly is one measure of the toxification of the biosphere by human activity (see Chapter III, Section 3; Likens 1991). At the Hubbard Brook Experimental Forest my colleagues have measured the lead concentrations in rain and snow and other components of forest and aquatic ecosystems since 1975 (Siccama and Smith 1978, Smith and Siccama 1981, Siccama et al. 1980). In 1975 the concentration of lead in rain and snow at Hubbard Brook averaged about 25 $\mu\text{g liter}^{-1}$. This value exceeds the value currently recommended by the US Environmental Protection Agency (EPA) for drinking water.

During the past 20 years or so, there has been a major curtailment in the use of lead additives in gasoline in the Northern Hemisphere. In 1977 the EPA sharply restricted the use of leaded gasoline by motor vehicles in an attempt to protect human health, and as a result lead concentrations in the atmosphere of the US have declined significantly. Lead concentrations in air decreased on average about 79% in 53 cities in the United States between 1976 and 1985 (US EPA 1985). Current values in rain and snow at Hubbard Brook average about 2 $\mu\text{g Pb liter}^{-1}$ (Fig. 14). Lead concentrations in ice and snow in Greenland also have decreased by a factor of about 7.5 during 1970 to 1990 (Boutron et al. 1991).

Table 4. Estimated annual global emissions (thousand metric tons) of selected metals to the atmosphere circa 1980. (From Galloway et al. 1982)

Metal	Human activity	Natural activity	Ratio of human to natural activity
Lead	2000	6	333
Zinc	840	36	23
Copper	260	19	14
Vanadium	210	65	3
Nickel	98	28	4
Chromium	94	58	2
Arsenic	78	21	4
Antimony	38	1	38
Selenium	14	3	5
Cadmium	6	0.3	20

Most of the incoming lead in precipitation at Hubbard Brook was held tightly in the highly organic forest floor of the ecosystem, and streamwater concentrations have been consistently low (1 to 2 $\mu\text{g Pb liter}^{-1}$) since 1975 (Fig. 14; Siccama and Smith 1978, Smith and Siccama 1981). Now, however, concurrently with decreasing atmospheric inputs, lead concentrations in the forest floor are declining (Fig. 14). Apparently, the lead in the forest floor is being complexed and transported to deeper soil horizons in associ-

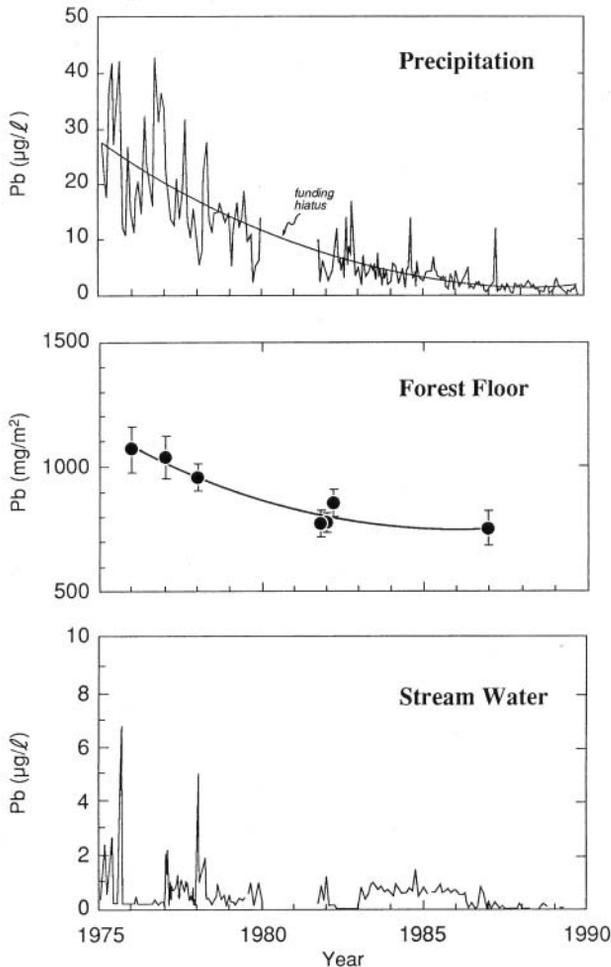


Fig. 14. Concentration of lead in precipitation, forest floor and stream water at the Hubbard Brook Experimental Forest from 1975 to 1989. Vertical bars represent standard deviations of the mean. (Data provided by T. G. Siccama)

ation with dissolved organic matter (DOM) as decomposition of organic matter occurs in the forest floor (Driscoll et al. 1988, Driscoll and Otton 1992). Whether this lead being deposited in the mineral soil will be permanently immobilized there or not is an important question. Acidification of the soil by nitric acid following experimental deforestation at Hubbard Brook did not result in the mobilization of lead (Fuller et al. 1988). But, what if DOM is remobilized as a result of some future disturbance, will this also remobilize the lead?

The pool of lead in soil is two orders of magnitude larger than lead accumulated in biomass above- and below-ground (Fig. 15). If net precipitation inputs were the only source of lead for the HBEF it would have required about 7 yr, 56 yr, and 680 yr, to accumulate the lead found in biomass, forest floor and total soil pools, respectively, assuming negligible lead in the pools at time zero and negligible cycling between these pools.

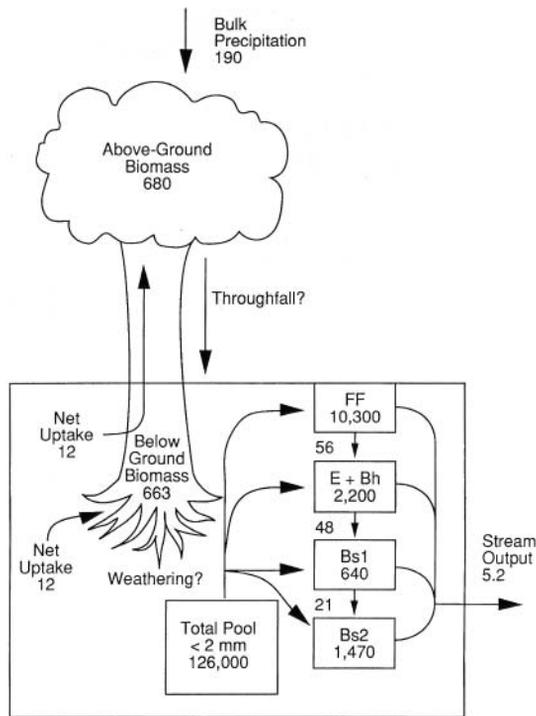


Fig. 15. Annual lead budget for a forest watershed-ecosystem at Hubbard Brook, characterizing the period 1985 to 1990. Pools (boxes) are in g ha^{-1} , transfers (arrows) in g/ha-yr . FF = forest floor; E, B_h , B_s = soil horizons. (From Driscoll and Otton 1992; modified)

The reduction in the dispersal of a toxic metal, such as lead, throughout landscapes of the Northern Hemisphere is an environmental success story. That is, the effects of governmental regulation, which reduced the use of lead additives in gasoline – additives that are technologically unnecessary – can be seen in the chemistry of rain and snow in a rural area, such as Hubbard Brook, or in remote areas, such as Greenland. Unfortunately, however, apparently the United States is exporting more lead additives on a yearly basis to developing countries than were burned annually in the United States prior to federal regulation (J. Nriagu, pers. comm., September 1989).

Sulfur. Other insights come from our long-term studies of sulfur at Hubbard Brook. There was a relatively large increase in sulfur dioxide emissions in the US from 1940 until the time of the passage of the Clean Air Act in 1970 by the Congress of the United States, after which emissions have decreased (Fig. 16). It now is mandated that total US emissions of SO_2 will decrease by 10 million tons (9.1 million metric tons) below the 1980 value by the year 2000, following legislative Amendments to the 1970 Clean Air Act, which were enacted during the fall of 1990 (see Chapter III, Section 3).

A statistically significant decrease in sulfate concentration in precipitation, as well as in wet deposition (Figs. 10 and 17), has occurred at Hubbard Brook since the beginning of our record in 1964–65. The decline in wet deposition of sulfate occurred primarily between 1964–65 and 1983–84, as deposition was relatively constant or even increasing from 1983–84 to

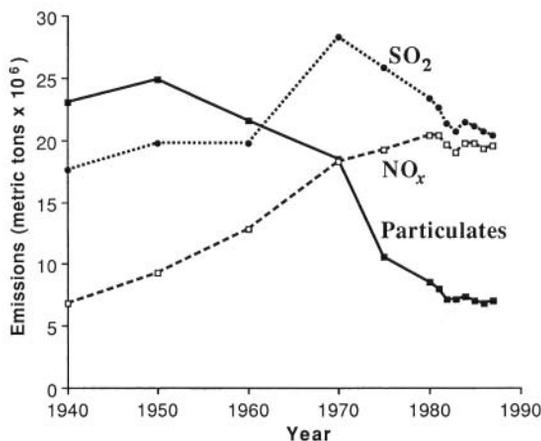


Fig. 16. Changes in SO_2 , NO_x and particle emissions for the United States during 1940–1987. (Data from US Environmental Protection Agency, 1989; National Air Pollutant Emission estimates 1940–1987. EPA-450/4-88-002. National Air Data Branch, Research Triangle Park, North Carolina)

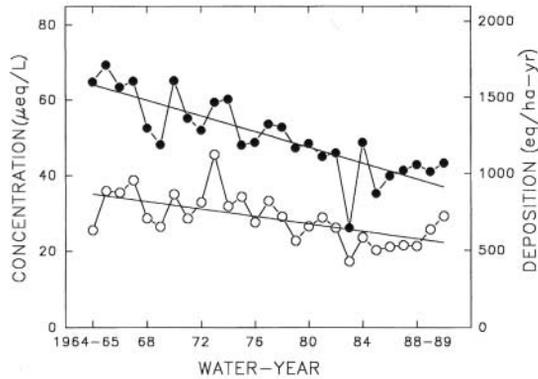


Fig. 17. Annual volume-weighted concentration (●) and annual wet deposition (○) of sulfate from 1964–65 to 1990–91 for Watershed 6 of the Hubbard Brook Experimental Forest. Probability for a larger F -ratio for both regression equations is <0.001 ; r^2 for SO_4^- concentration regression is 0.68, and for SO_4^- deposition regression is 0.43

1989–90 (Fig. 17). These long-term decreases in atmospheric input to the ecosystem appear to be associated with reductions in sulfur dioxide emissions throughout the eastern US after 1970 (Calvert 1983, Likens et al. 1984, Hedin et al. 1987, Butler and Likens 1991). This relation also has been observed at other sites in the US with shorter records (Butler and Likens 1991, see also p. 131 ff.).

The decrease of sulfate concentration in precipitation at Hubbard Brook also is correlated with an increase in the pH of precipitation (Figs. 10 and 11) and with decreases in sulfate concentrations in stream water (Driscoll et al. 1989b). This information was of much interest to decision makers who were debating during the past several years whether a costly reduction in SO_2 emissions would result in a significant decrease in SO_4^- concentrations in precipitation, and thus reduce the impact of acid rain on natural ecosystems. In fact, a US National Academy of Sciences report in 1983 (Calvert 1983) suggested on the basis of long-term data from Hubbard Brook that there would be a direct linear relationship between decreases in SO_2 emissions and sulfate concentrations in precipitation (Chapter III, Section 3).

Using these long-term data and the mass-balance approach, it was possible to estimate the annual dry deposition of sulfur for watershed-ecosystems of the Hubbard Brook Experimental Forest during a 23-yr period (1964–1987):

$$\text{Dry deposition} = \text{stream output} + \text{gaseous loss} + \text{net storage} - \text{wet deposition} - \text{weathering release}$$

(see Fig. 18). Annual values of dry deposition at Hubbard Brook were estimated to range between 87 and 780 eq SO₄⁻/ha-yr during this period with a mean of 410 eq SO₄⁻/ha-yr; s_x = 34 (Likens et al. 1990b). Unfortunately, quantitative values for gaseous loss are not available, but I estimate that the dry deposition value would be increased by <20 eq SO₄⁻/ha-yr if the gaseous losses were included. The two major terms in the mass-balance equation are wet bulk precipitation input (705 eq SO₄⁻/ha-yr) and streamwater output (1040 eq SO₄⁻/ha-yr). Thus, when the sulfate output in stream water is plotted against the sulfate input in wet bulk precipitation, a strong, linear relation is obtained (Fig. 19). This regression line, however, falls above the 1:1 line, which means that more sulfur is lost from the ecosystem than is added in wet bulk precipitation. Because these are the major terms in the mass balance and the other terms are relatively small and tend to cancel, the regression analysis provides another estimate of dry deposition for watershed-ecosystems at Hubbard Brook. These two approaches, the regression analysis of wet bulk precipitation inputs and stream

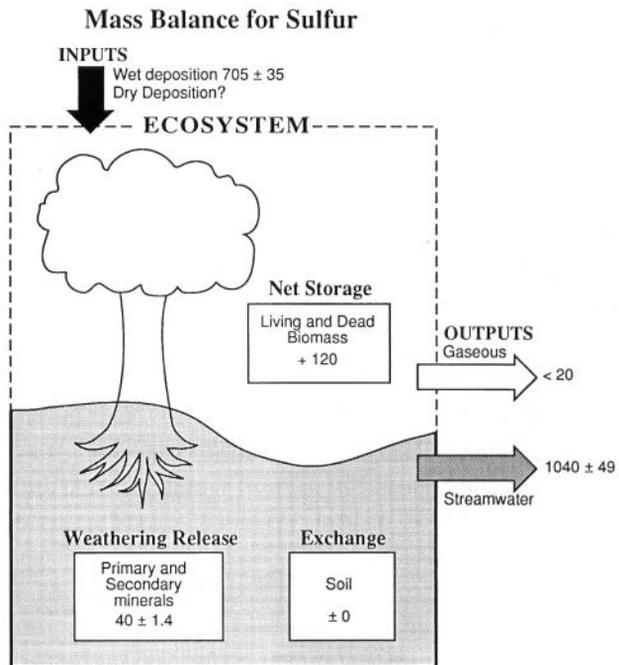


Fig. 18. Sulfur mass balance terms used to estimate dry deposition for Watershed 6 of the Hubbard Brook Experimental Forest from 1964 to 1986

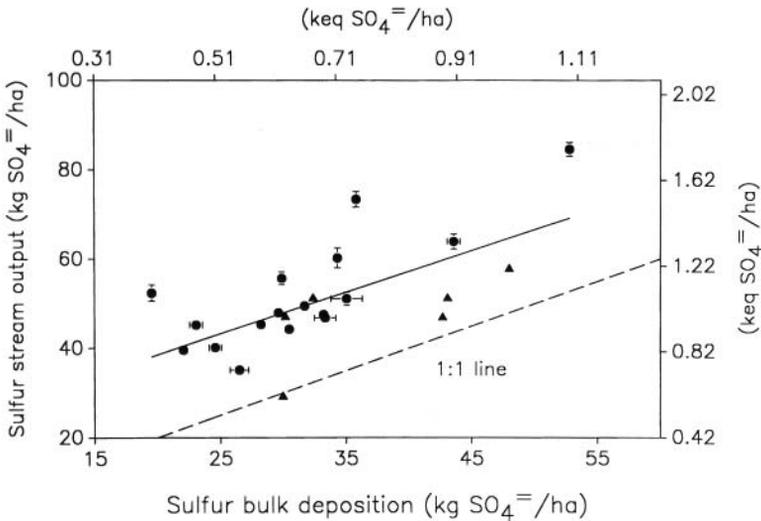


Fig. 19. Relationship between average annual input of SO_4^- in bulk wet precipitation and annual output in stream water for Watersheds 1, 3, 5 and 6 of the Hubbard Brook Experimental Forest from 1964–65 to 1985–86. Data on stream water SO_4^- are as follows: Watershed 1, 1971–87; Watershed 3, 1973–87; Watershed 5, 1973–83; and Watershed 6, 1965–87. Regression line (—) is $Y = 0.934X + 413$ (probability for a larger F -ratio = <0.001 , $r^2 = 0.43$). \blacktriangle = data for Watershed 6 only (1964–1969), thus annual values for these years are not replicated; \bullet = mean value for all watersheds available ($n = 2$ to 4) with standard error bars; for some of these mean values the SE was very small and cannot be differentiated from the dot. (From Likens et al. 1990b)

outputs, and the annual mass-balance method, gave similar average values for forested Watershed 6 (430 and 410 eq $\text{SO}_4^-/\text{ha}\cdot\text{yr}$, respectively, for this 23-year period; Likens et al. 1990b). Dry deposition contributed about 37% of total (wet plus dry) annual sulfur deposition, varying from 12% in 1964–65 to 61% in 1983–84.

These data also provided a unique opportunity to evaluate spatial (between watershed-ecosystems) and temporal (between years) variability. Four adjacent watershed-ecosystems responded to different loadings of atmospheric sulfur very similarly (Fig. 19). Whereas only 2% of the variance in sulfate output in stream water was attributed to differences between watersheds, 97% of the variance was due to differences between years (Likens et al. 1990b).

Dry deposition is a very difficult flux to measure quantitatively in natural ecosystems, particularly those with rough topography, and estimates of this important input for intact terrestrial ecosystems are rare (Likens et

al. 1990b). Yet, the magnitude of dry deposition, and its temporal and spatial variability, are critical to attempts to understand the function of ecosystems as well as for decision makers concerned with environmental problems, such as acid rain. Insights from SER utilizing the ecosystem approach can add significantly to this understanding. It is apparent from these data and others that estimates of dry deposition are not particularly meaningful unless they are done over several (5 to 10) years (e.g. Hultberg and Likens 1992).

Base cations. The long-term biogeochemical data from Hubbard Brook also revealed a statistically significant decline in the sum of base cations (Ca^{++} , Mg^{++} , Na^+ , K^+) in precipitation since the beginning of our SER in 1963 (Fig. 20; Driscoll et al. 1989a). Essentially all of the decline occurred between 1963–64 and 1971–72, as concentrations averaged about $10 \mu\text{eq liter}^{-1}$ thereafter, with relatively little interannual variability.

Most of the long-term decrease in concentration of base cations in precipitation was caused by a decrease in calcium concentration, and particularly during 1963–64 to 1972–73 (Fig. 21). Calcium concentrations decreased by about $10 \mu\text{eq liter}^{-1}$ during this 10-yr period and thus accounted for about 33% of the total long-term (28 yr) decline in the sum of all four base cations. Although statistically significant long-term declines were observed for each of the base cations, most of the decline occurred during the early years of the record (Fig. 16).

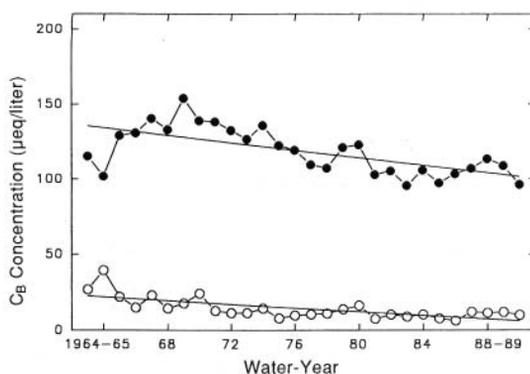


Fig. 20. Long-term changes in concentrations of the sum of base cations, C_B (Ca^{++} , Mg^{++} , K^+ , Na^+), in precipitation (\circ) and stream water (\bullet) for Watershed 6 of the Hubbard Brook Experimental Forest between 1963–64 and 1990–91. Probability for a larger F -ratio for both regressions is <0.001 ; r^2 for base cations in precipitation is 0.48, for stream water 0.39

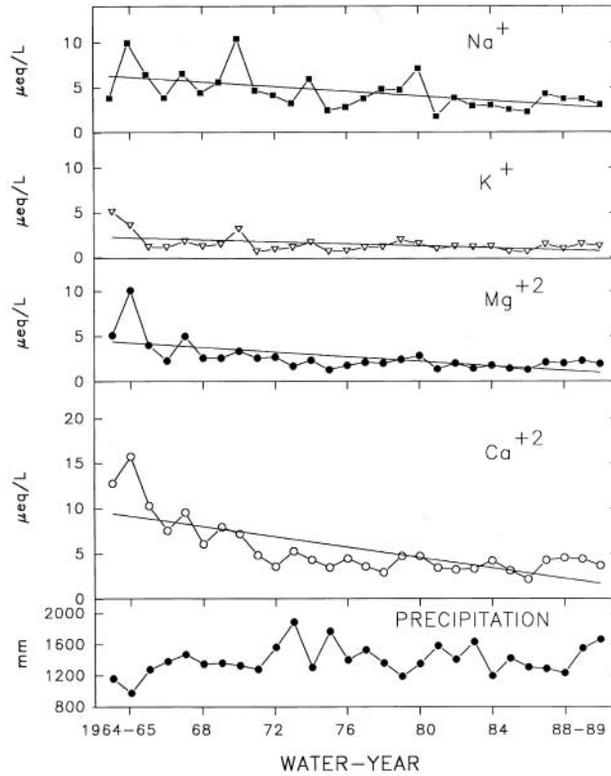


Fig. 21. Long-term changes in concentrations of Na^+ , K^+ , Mg^{++} and Ca^{++} in precipitation and in amount of precipitation for Watershed 6 of the Hubbard Brook Experimental Forest between 1963-64 and 1990-91. Probability for a larger F -ratio for all regression lines is <0.05

Although the reasons for the decline in concentrations of base cations are unclear, there are several possibilities (Table 5). It is usually assumed that the main source for such cations in the atmosphere is from crustal particles originating from agricultural fields, unpaved roads and deserts (e.g. Tamm and Troedsson 1955, Rahn et al. 1979, Stensland and Semonin 1982, Gatz et al. 1985, 1986), and that soil particles are not transported long distances in the atmosphere (e.g. Rahn et al. 1979). Small dust particles ($<10 \mu\text{m}$ in radius) from deserts, such as the Sahara, however, apparently have been transported widely throughout the atmosphere (Rahn et al. 1979). Of the various potential sources of dust (Table 5), there is little support at Hubbard Brook for changes in the influence of cement plants, changes in

Table 5. Potential sources for change in atmospheric deposition of base cations at Hubbard Brook

-
- (1) Reduction in particulate emissions from:
 - (a) Cement production
 - (b) Electrical utility power plants and smelters
 - (2) Changes in agricultural activities
 - (3) Conversion of unpaved roads to paved roads
-

agricultural activity or changes in use of unpaved roads nearby the Hubbard Brook Experimental Forest (Driscoll et al. 1989a). In fact, unpaved roads within the HBEF are used to a greater extent currently than they were two to three decades ago, because of a larger number of researchers that are involved in the HBES currently. Thus, the most likely explanation for the decline in base cations in precipitation is a regional/national decline in particle emissions (Fig. 16), possibly largely due to increased control of emissions from industrial processes and use of particle scrubbers in power plant and smelter smokestacks as a result of the 1970 Clean Air Act (Table 6).

The chemistry of stream water at Hubbard Brook also has changed during the period 1963–1990. The regression for the sum of base cation concentration with time, based on long-term data, is statistically significant,

Table 6. Estimates of particulate matter emissions (metric tons $\times 10^6 \text{ yr}^{-1}$) for the United States by source category. (Data from US Environmental Protection Agency, 1989; National Air Pollutant Emission estimates 1940–1987. EPA-450/4-88-002. National Air Data Branch, Research Triangle Park, North Carolina, USA)

Source	1970	1987	% Change
Industrial processes	10.5	2.5	-76
Fuel combustion	4.6	1.8	-61
Solid waste incineration	1.1	0.3	-73
Miscellaneous*	1.1	1.0	-9
Transportation	1.2	1.4	+17
Total	18.5	7.0	-62

*For example, forest fires

but shorter-term patterns also are evident. For example, concentrations generally increased from 1963–64 to 1970–71, then rather steadily declined to about 1986–87. Although the pattern of decline in concentration for the sum of base cations in stream water is different than that in precipitation, the magnitude of decline (about $30 \mu\text{eq liter}^{-1}$) is similar (Fig. 20).

Again the long-term pattern for sum of base-cation concentrations in stream water is largely determined by changes in calcium concentrations. Calcium concentrations in stream water generally increased from 1963–64 to 1969–70, and declined thereafter (Fig. 22). Statistically significant, long-term declines were observed for Na^+ and Mg^{++} , but the changes in magnitude were small. No long-term trend was observed for potassium concentrations in stream water (Fig. 22).

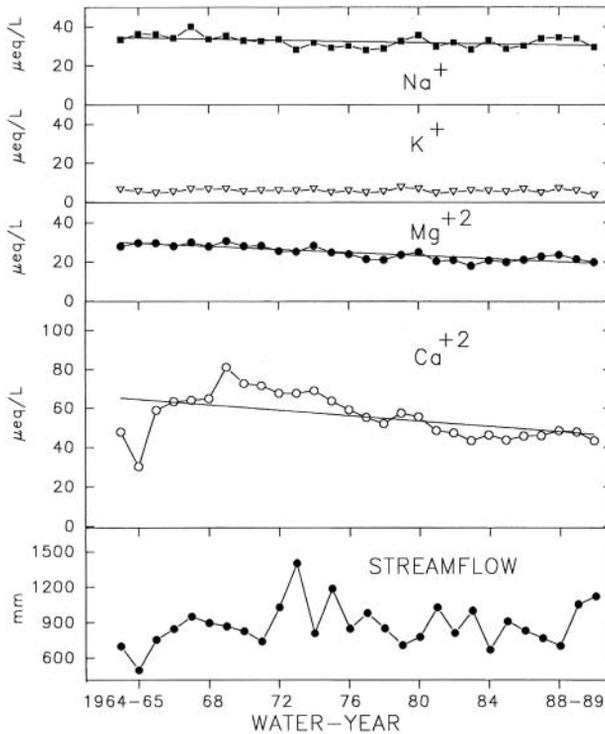


Fig. 22. Long-term changes in concentrations of Na^+ , K^+ , Mg^{++} and Ca^{++} in stream water and in amount of stream water for Watershed 6 of the Hubbard Brook Experimental Forest between 1963–64 and 1990–91. Probability for a larger F -ratio for all regression lines is <0.05

These patterns only became apparent because of the long-term data (Driscoll et al. 1989a). Thus, in spite of the enormous complexity of vegetation, soil and bedrock within these forest ecosystems, these correlations suggest a highly regulated system and a long-term relation between precipitation inputs and stream water outputs of base cations.

There are several possibilities, however, to explain these long-term patterns of base cation concentrations in stream water (Table 7). The evaluation of these possibilities at Hubbard Brook is as follows: There are no data to suggest that (1) hydrologic flow paths have changed, i.e. that water has tended to flow through the ecosystem in some different way that would affect streamwater chemistry, (2) there have been long-term increases in the accumulation of base cations by biomass, or (3) there has been a long-term decline in weathering (Driscoll et al. 1989a).

Obviously, changes in pools of exchangeable cations and decreases in SO_4^- leaching (the salt effect) in the soil could contribute to the decline in stream concentrations of base cations (Driscoll et al. 1989b). Unfortunately, there are no quantitative data to evaluate whether there has been a long-term change in the type or rate of soil exchange reactions at Hubbard Brook. Because of its spatial heterogeneity, the soil exchange complex is a very difficult component to assess at the scale of an ecosystem. Based on correlation analysis, however, the decline in base cation concentration in precipitation at Hubbard Brook explained from 77 to 82% of the variability in the decline of base cations in stream water (Driscoll et al. 1989a).

The internal rate of generation of Ca^{++} and other base cations to drainage water is relatively low at the HBEF because of the small pools of exchangeable base cations and the low abundance of readily weatherable minerals.

Table 7. Potential causes for long-term decline in base cation concentrations in streamflow at Hubbard Brook

-
- (1) Long-term changes in hydrologic flowpaths
 - (2) Long-term increases in biomass accumulation
 - (3) Long-term decline in weathering
 - (4) Decreased displacement of base cations from the soil-exchange complex
 - (5) Reduction in atmospheric inputs
-

This limited release of base cations at the HBEF is important because the supply of base cations by cation exchange and weathering contribute to the generation of acid neutralizing capacity in stream water and the neutralization of inputs of acidic deposition to the ecosystem (Johnson et al. 1981, Driscoll and Likens 1982). Atmospheric deposition of sulfuric acid is the dominant source of acidity for the HBEF (external inputs plus internal production; Driscoll and Likens 1982). Yet the long-term decline in sulfate concentrations in precipitation (Figs. 10 and 17) has not resulted in an increase in stream pH, despite decreasing concentrations of sulfate in stream water (Driscoll et al. 1989a). Rather, a stoichiometric decline in the sum of base cations has coincided with the decrease in sulfate concentrations, preventing any long-term decrease in stream acidity.

Because of the marked decline in the atmospheric deposition of base cations, total ecosystem inputs of base cations to the HBEF are currently near the lowest value for the last 28 years (Driscoll et al. 1989a). Depending upon the affinity of these base cations for cation exchange surfaces in the soil, the decreased inputs of base cations could be reflected either as decreased base cations in stream water or as a decrease in base saturation of soils at HBEF (Driscoll et al. 1989b). Both of these processes would increase the sensitivity of surface waters to inputs of strong acids from the atmosphere. As a result, it appears that the expected recovery of acidified surface waters at Hubbard Brook, due to decreased loading of sulfate from the atmosphere, generally has been retarded because of declining atmospheric inputs of basic substances (Driscoll et al. 1989a). These surprising findings represent important insights from our SER at Hubbard Brook, and have major management implications.

Swedish workers (Hällbacken and Tamm 1986, Tamm and Hällbacken 1986, 1988) have shown, from careful comparison of historical and recent data obtained from the same plots, that an appreciable acidification of forest soils in Sweden has occurred during the past 50 to 60 years from atmospheric deposition of strong acids, primarily sulfuric acid. This result of SER is very important ecologically because soils develop slowly, and presumably would recover slowly following a reduction in deposition of atmospheric pollutants. Lakes, on the other hand, because of the flushing by incoming water, would be expected to reverse acidification trends much more rapidly (e.g. Gunn and Keller 1990).

Nitrogen. There is no long-term, statistically significant relation between emissions of NO_x in the eastern US and concentrations of NO_3^- in precipitation at Hubbard Brook. Similarly, no relation was found for other

sites measuring precipitation chemistry in the eastern US (Butler and Likens 1991). Concentrations of NO_3^- in precipitation at Hubbard Brook increased from 1964 until about 1971 and then have averaged about $25 \mu\text{eq liter}^{-1}$ until the present (Fig. 10).

The long-term, seasonal pattern of nitrate in stream water at Hubbard Brook is highly predictable (Likens et al. 1977, 1985a). The nitrate concentrations in stream water consistently are low during the vegetative growing season and high during the winter months (Fig. 23). Nitrate concentrations averaged for June, July, August, September and October as compared to averages for January, February, March and April show this pattern clearly (Fig. 24). Note, however, that during 1970–1977 the winter concentrations of nitrate were much higher than either previously or after this period in the long-term record (Figs. 23 and 24). A long-term plot of the total inorganic nitrogen (nitrate plus ammonium), in precipitation and in stream water, provides an unexpected insight (Fig. 25). Although nitrogen inputs have averaged about 500 eq N/ha-yr since about 1965, during the first 5 years of the record, the precipitation input of inorganic N was much higher than the streamwater output. As a result, this nitrogen-limited system was being “fertilized” by inorganic nitrogen from the atmosphere. Then during an 8-yr period, 1968–69 to 1975–76, outputs in stream water were much higher, and in one year even exceeded precipitation inputs. These higher

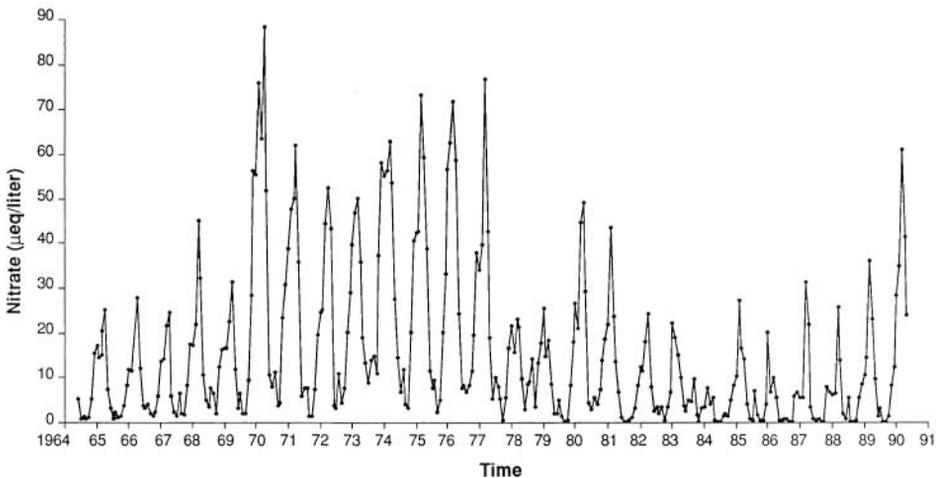


Fig. 23. Average volume-weighted monthly concentrations of nitrate in stream water from Watershed 6 of the Hubbard Brook Experimental Forest. (From Likens et al. 1977; modified and updated)

output values were dominated by the higher NO_3^- concentrations in winter during these years (Fig. 24). More recently the pattern has reverted to the original pattern, although the most recent data suggest an upturn again in streamwater losses (Fig. 25). An alternative to this step-like pattern is an interpretation that losses of nitrogen generally increased from 1964 to about 1975, declined until about 1985, and then increased, roughly paralleling the pattern of precipitation inputs, and suggesting a larger role for changes in precipitation inputs in determining this long-term pattern for nitrogen. In any event, the ecosystem seems to be behaving like a giant electrical capacitor: storing up inorganic nitrogen, then discharging it, and then storing it again. As yet we have no quantitative explanation for these long-term patterns. Nevertheless, these patterns are of critical importance to understanding the biogeochemistry and metabolism of forest and associated aquatic ecosystems, and currently are the focus of several research initiatives at Hubbard Brook.

Based on data for the total period, June 1964 through December 1990, 2.4 times more nitrogen was added in wet deposition to watershed-ecosystems at Hubbard Brook than was lost in stream water. On average,

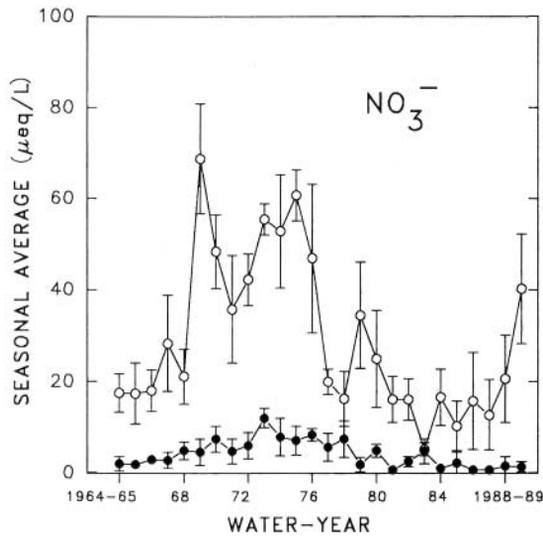


Fig. 24. Volume-weighted, average nitrate concentrations ($\mu\text{eq liter}^{-1}$) for Jun, Jul, Aug, Sep and Oct (●) and for Jan, Feb, Mar and Apr (○) from 1964–65 to 1989–90 for Watershed 6 of the Hubbard Brook Experimental Forest. Vertical bars represent standard deviations of the mean

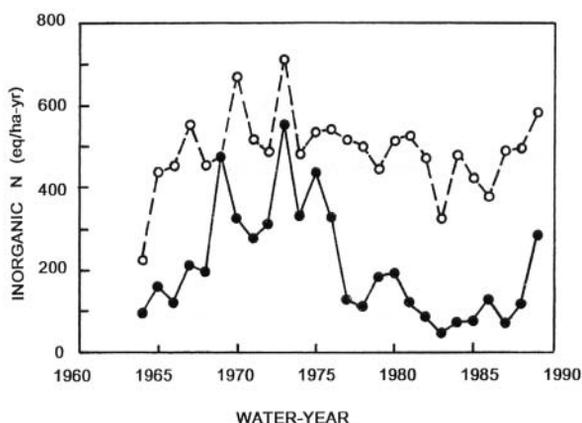


Fig. 25. Annual fluxes (eq/ha-yr) of total inorganic nitrogen in precipitation (○) and stream water (●) in Watershed 6 from 1964–65 to 1989–90

69.5% of these total inorganic inputs (183 kg N ha^{-1}) was added as $\text{NO}_3\text{-N}$ and 30.5% as $\text{NH}_4\text{-N}$. Presumably because NH_4^+ is a preferred nitrogen source for plants and because of microbial nitrification, this ratio was observed to increase even further in streamwater outputs (94% of total outputs as $\text{NO}_3\text{-N}$ and 6% as $\text{NH}_4\text{-N}$). In fact, nitrate-nitrogen inputs in wet deposition were 1.7 times greater than the total nitrogen loss ($76.4 \text{ kg N ha}^{-1}$) in stream water during the entire period. In addition, dry deposition of nitrogen might add 2.5 kg N/ha-yr to the atmospheric inputs (G. Lovett, pers. comm.). Gaseous losses of nitrogen are believed to be small at Hubbard Brook (Bormann et al. 1977, Roskoski 1977). Based on these long-term data, forest ecosystems and associated aquatic ecosystems at Hubbard Brook have been large net sinks for inputs of atmospheric nitrogen during the period of our SER.

These fluxes and their temporal patterns are important to current ideas and controversies about nitrogen-saturation in systems that have large inputs of nitrogen from the atmosphere (e.g. Aber et al. 1991). There are many definitions of nitrogen saturation, but a useful one generated at a recent Institute of Ecosystem Studies' workshop is, "the state at which ecosystem outputs of nitrogen roughly equal or exceed inputs of nitrogen during an appropriate time period." Nitrogen saturation has important implications for the management and protection of natural ecosystems, and for water quality considerations (pp. 97 to 103).

Animal populations in ecosystems

Richard T. Holmes and colleagues have monitored the bird populations at Hubbard Brook since 1969 (Fig. 26). The number of birds decreased in the early 1980's to a size less than 50% of the number that had been present a decade earlier. Currently the population size appears to be increasing somewhat. Holmes proposed that the large decrease during the 1970's might be due to deterioration of the wintering habitat (e.g. in Jamaica, West Indies) for the migratory species of this population. Through SER, however, it has been concluded that the cause is not this simple, and Holmes and colleagues are turning their attention as well to long-term fluctuations in food resources and other factors (e.g. natural changes in habitat structure due to ecosystem development, nest predation, competition between species) during the breeding season at Hubbard Brook for the answer (Holmes 1990a, b, c).

Douglas Gill (1983) and colleagues have studied the long-term population dynamics and behavior of red-spotted newts *Notophthalmus viridescens* in northern Virginia. Gill assumed that juvenile salamanders living in terrestrial habitats would mature in a year or two, and then return to breed in ponds that were being monitored. Only after 6 to 7 years, however, did his marked individuals return to the ponds (see Likens 1983). Obviously insights about the metabolism, behavior and biogeochemical role of these animals required SER.

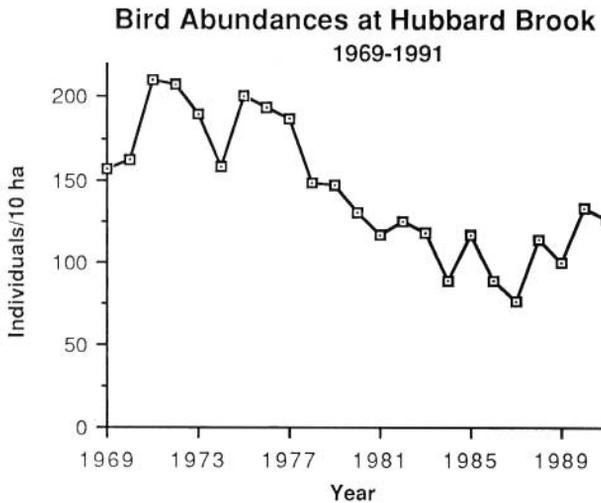


Fig. 26. Bird populations at Hubbard Brook from 1969 to 1991. (Data from R. T. Holmes)

Lake ecosystems

Lakes are highly variable in biology, chemistry, hydrology, depth, watershed characteristics, and so forth. For example, adjacent lakes may be brown stained or clear. Some of this complexity is addressed on p. 65 ff., but here I will provide some examples of SER that have contributed to the understanding of this complexity.

Salt pollution. The use of salt (NaCl) for de-icing of roadways during the winter is a common practice in the United States and other countries. This salt, which is added to surfaces of roadways, often finds its way to surface waters. Our SER on Mirror Lake, New Hampshire (Likens 1985b) provides an example. An interstate highway (I-93) was constructed through the watershed for Mirror Lake (Fig. 4) during 1969–71. This portion of the watershed for the lake is drained by Northeast Tributary. Some 96 metric tons of salt (mostly NaCl) are applied to the 1.2-km section of the interstate highway within the Mirror Lake watershed each year. In spite of special efforts during construction of the highway to divert the salt in drainage water away from the lake, long-term monitoring has shown that large amounts of salt now are draining into this small oligotrophic lake (Fig. 27; Bormann and Likens 1985, Bukaveckas and Likens 1992). Following the completion of construction of I-93 in 1971, no significant trend for increases in Cl^- concentration in Northeast Tributary was observed for several years, but subsequent to about 1973 concentrations have increased dramatically (Fig. 27). Currently, average concentrations of Cl^- in this tributary are about 60 times higher than they were prior to the construction of the interstate highway. Increases in concentration of Cl^- in the lake, as measured at the outlet, were delayed for about 3 years, but have followed the same pattern as in the Northeast Tributary (Fig. 27). The Cl^- inputs have been diluted by the volume of the lake and the overall increase in concentration in the lake has been less (about 3-fold). The ecological effect of this input of salt on the Mirror Lake ecosystem is a part of our ongoing SER.

The Adirondack Park of New York State is the largest park in the conterminous United States. The Park was established in 1892 to help protect natural areas in this mountainous region. Recent studies (Driscoll et al. 1991) have estimated that about 28% of the lakes in the Park now have been impacted by salt (impacted lakes are defined as those lakes with Cl^- concentrations greater than $20 \mu\text{eq liter}^{-1}$). Although the actual source of this salt is unknown, the correspondence of salt-impacted lakes in the Park with nearby roadways is striking (Fig. 28).

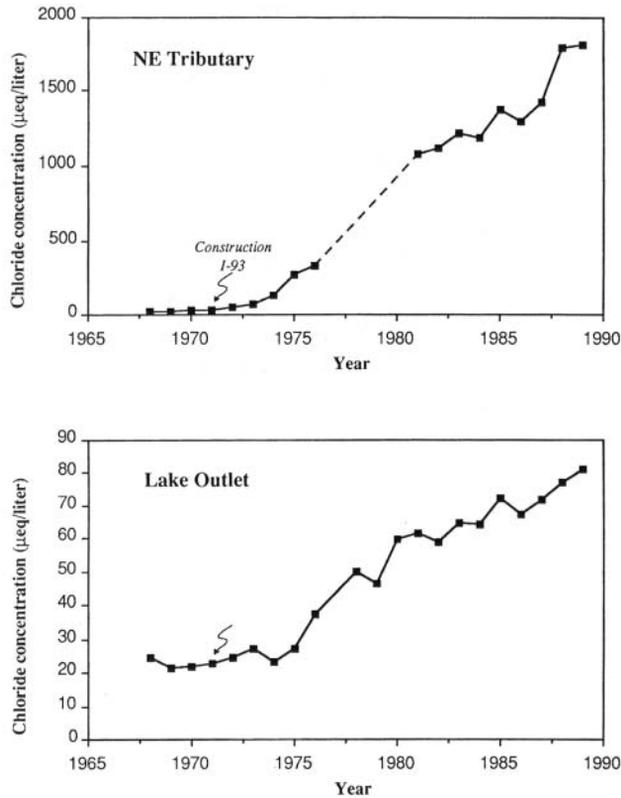


Fig. 27. Average, annual concentration of chloride in Northeast Tributary and the outlet to Mirror Lake during 1967 to 1989. Interstate highway I-93 was constructed through the watershed of Northeast Tributary in 1971

Lake Vättern, in Sweden, is one of the largest oligotrophic lakes in Europe, but it has changed in many ways during the last 25 years (Persson et al. 1989). For example, its salt content increased by 23% during 1939 and 1970–74, and by 8% during 1974 and 1986 (Persson et al. 1989). Again the source has not been established, but salt used for de-icing roads may be a factor. De-icing of roads in Sweden was started in the early 1960's and increased to about 350 000 tons of salt yr^{-1} by 1980 (Löfuendahl 1990). The transport of sodium and chloride in rivers of Sweden increased from 1969 to 1983 and was attributed largely to the use of salt on roads for de-icing (Löfuendahl 1990). The usefulness of data from SER to evaluate these assumed anthropogenically-caused changes in lakes and rivers is critical.

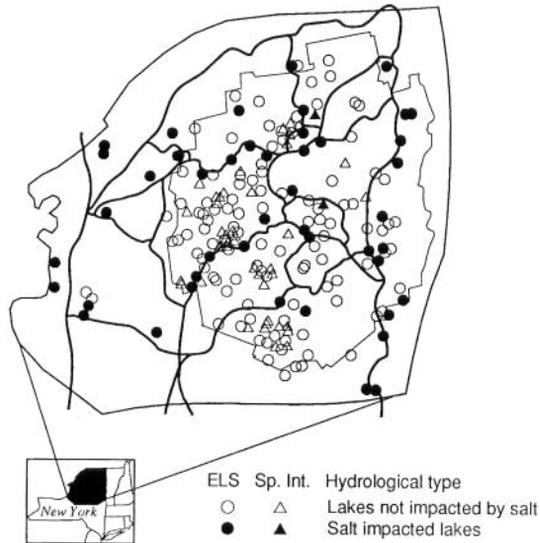


Fig. 28. Salt-impacted lakes ($\text{Cl}^- > 20 \mu\text{eq liter}^{-1}$) in the Adirondack Mt. region of New York State, USA. Data were collected as part of the Eastern Lake Survey (ELS) and special interest (Sp. Int.) lakes. Heavy lines indicate major roads; thin line denotes Adirondack Park boundary. (From Driscoll et al. 1991; modified)

Eutrophication. Long-term limnological studies of Lake Washington near Seattle, Washington (USA), are another classic example of sustained ecological research. Long-term changes in the chemistry and biology of Lake Washington have occurred largely because of in-lake responses to human disturbances within the watershed of the lake. These limnological changes have been studied and documented carefully by W. T. Edmondson and colleagues.

Edmondson's Lake Washington story is a wonderful example of SER, and the overall insights that it provided would not have been available from discrete, short-term studies. Parts of this story (shorter-term reports) are published in numerous papers (e.g. Edmondson 1972b, Edmondson and Lehman 1981, Edmondson and Litt 1982), and the current, long-term perspective is summarized in Edmondson (1990). "Current, long-term" is a contradiction, but this, as are most SER's, is an ever-unfolding story. Signals that eutrophication was occurring in the lake were observed first in 1950. These included a doubling of phosphate concentrations since measurements began in 1933, and a small increase in oxygen consumption in deep waters. By 1955, a well-known "nuisance" blue-green alga (*Oscillato-*

ria rubescens) was observed. Because of public concern about the deterioration of water quality in the lake, the municipality of metropolitan Seattle issued bonds to finance the construction of a system to divert phosphorus-rich sewage away from the lake. Diversion began in 1963 and was completed in 1968.

As a result of the decrease in nutrient input to the lake, *Oscillatoria rubescens* changed from being the dominant form in the phytoplankton, to being scarce by 1976 and absent in 1977. In 1976 the lake suddenly became much more transparent to solar radiation. In part, this increased clarity was due to the disappearance of *O. rubescens*, but the abrupt change also correlated with a population explosion of *Daphnia* spp., which before 1976 was present only in small numbers. The *Daphnia* are effective at grazing small algae, thereby helping to clarify the water. But what caused the sudden increase in *Daphnia*?

Based on the other data from this comprehensive SER, Edmondson interpreted these changes as follows: numbers of *Daphnia* had been suppressed by *Neomysis mercedis*, a highly specialized and effective predator on *Daphnia*, between 1933 and 1967; *Daphnia* was suppressed by *Oscillatoria rubescens*, probably by interfering with the food-gathering filtration system of *Daphnia*, between 1955 and 1975. Numbers of *Neomysis* decreased in the mid-1960s presumably because of predation by a fish, the long-fin smelt *Spirinchus thaleichthys*, which spawns in the Cedar River, a major tributary to the lake. Fish spawning habitat was improved in the Cedar River in the early 1960's because of a bank stabilization program and cessation of dredging. These changes apparently increased the abundance of smelt in the lake during this period. Undoubtedly this story will continue, especially since human use of the lake's watershed is increasing (Edmondson 1972b, Edmondson and Lehman 1981, Edmondson and Litt 1982).

The difficulty with a study like Edmondson's is that it is necessary to follow the changes in phytoplankton, zooplankton, fish, and other organisms, on a species basis comprehensively and for long periods. Studies of this type require dedicated specialists that can recognize species consistently during long periods, and it is very difficult to maintain funding and trained personnel for such long-term studies.

Lake Tahoe is an ultra-oligotrophic lake, in the Sierra-Nevada Mountains on the border of California and Nevada. This lake has changed dramatically in the last three decades, primarily because of human disturbance, such as deforestation, construction of housing, roads, ski areas and

leachates from septic systems, in the watershed for the lake. Fortunately, sustained ecological research by Charles Goldman and colleagues on this lake has revealed much about what happened (e.g. Goldman 1988, 1990).

The annual primary productivity of Lake Tahoe has increased at a rate of $\sim 6\% \text{ yr}^{-1}$ since 1967. It required 5 years of record to establish a statistically significant trend for these data. This increase in primary productivity was correlated with increases in human population in Tahoe basin. The water of this ultra transparent lake is becoming less clear, but it required 6 years of data to establish a statistically significant trend of decreasing water transparency. The secchi-disk depth declined from about 30 m in 1958 to about 24 m in 1988, or at a rate of 0.37 m yr^{-1} between 1968 to 1986 (Goldman 1988, 1990). Many other important changes in species composition, metabolism and biogeochemistry have been documented by SER in Lake Tahoe during this period (Goldman 1988, 1990).

During the late 1960's and early 1970's, major scientific and public concerns were raised about the anthropogenic pollution and eutrophication of the Laurentian Great Lakes, particularly Lakes Erie, Ontario and Michigan. Relatively few long-term data were available, however, to evaluate the major changes that were occurring in the structure and function of these ecosystems. A major public "experiment" was started in early 1970 when the governments of Canada and the United States joined forces through the International Joint Commission (IJC) to reduce the loading of phosphorus to these lakes. Now, on the basis of long-term data it appears that Lakes Erie and Ontario are responding to the reductions in phosphorus loading (e.g. Makarewicz and Bertram 1991, Wolin et al. 1991). For example, in Lake Erie there has been a decline in the total phosphorus and chlorophyll concentrations, in nuisance algal species in the open water, and improvements in deep-water dissolved oxygen concentrations (Makarewicz and Bertram 1991).

Long-term data show that there has been a steady increase in nitrogen concentrations in Lake Vättern, Sweden, since about 1965 when measurements were begun (Fig. 29). The causes of this long-term increase are unclear, but may be the result of increased use of nitrogenous fertilizers for agriculture, increased sewage inputs, and increased amounts of nitrogen from atmospheric deposition (Persson et al. 1989; see also p. 97 ff.). During the same period, data from Lake Vättern also show long-term changes in the DDT and PCB concentrations in tissues of fish living in the lake (Persson et al. 1989). Decline in DDT and PCB's within fishes of Lake Vättern are correlated with Sweden's ban or limitation on the use of both

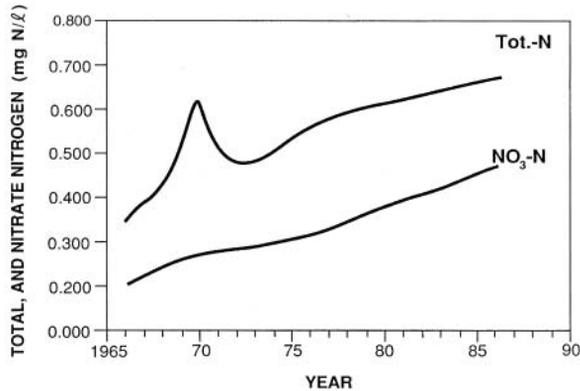


Fig. 29. Generalized growing season medians of total nitrogen and nitrate-nitrogen in Lake Vättern, Sweden during 1966 to 1986. (From Persson et al. 1989; modified)

PCB's and DDT. These reductions are another example of insights gained from sustained ecological research, as well as an environmental success story, in which the effects of governmental regulation can be seen in lowered levels of a toxic chemical within the general environment.

Atmospheric Carbon Dioxide

A classic example of sustained research is the long-term measurement of carbon dioxide concentrations in the atmosphere at the Mauna Loa Observatory in Hawaii by David Keeling. This record was started in 1958 (Keeling 1960, 1973) and is the longest *continuous* record of carbon dioxide available (Fig. 30). I will make two points regarding this particular record. When Keeling began to make CO₂ measurements at the South Pole in 1957, and in Hawaii in 1958, he did something very important. He took the calibration and standardization of his instruments seriously. He spent two years constructing a device so that he could standardize measurements in the future. At Hubbard Brook we adopted a policy at the beginning of our studies that if we were to change a method of chemical analysis for whatever reason, we would overlap the new method with the previous method for a long period (about 12 months) before making any permanent change in methodology. Unfortunately, such intercalibration between methods is not done frequently in long-term studies. Because such precautions are almost never taken, there often are different types of "long-term" measure-

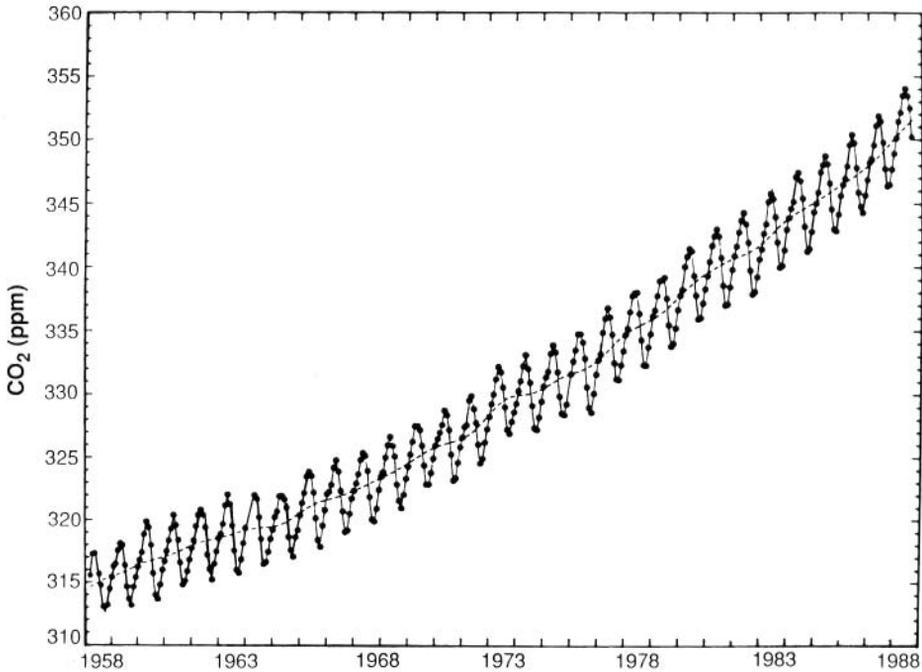


Fig. 30. Monthly mean concentration of atmospheric CO₂ at Mauna Loa Observatory, Hawaii. Dashed line represents annual averages. (Data were collected by C. D. Keeling and T. P. Whorf, and provided by the Carbon Dioxide Information Analysis Center, Oak Ridge, Tennessee)

ments, done by different people, by different methods, and often it isn't possible to know if individual data throughout a long-term record were comparable or not. One of the reasons the CO₂ record from Mauna Loa is believed is because Keeling was careful, and with foresight prepared to calibrate future measurements.

The other point is obvious (with hindsight). After about six years of tedious measurement, I could imagine Keeling wondering to himself whether he should continue. But he didn't stop, and in spite of much difficulty in trying to maintain funding, he has continued to measure CO₂ concentrations at Mauna Loa until the present. As a result, there is now available one long-term record of CO₂ for the atmosphere, which is enormously valuable for evaluating global climate change. Carbon dioxide is one of the important "greenhouse" gases and is thought to contribute to global warming and climate change (e.g. Keeling 1960, 1973, Ember et al. 1986). Shorter-term records of CO₂ concentration also are available for

Point Barrow in Alaska, American Samoa, and the South Pole, and they all show similar patterns of increase, and annual fluctuation, in the Earth's atmosphere (Gammon et al. 1985). Only with the accumulation of such data and interpretation about what they mean, does sustained research begin to provide new insights.

Alternatives to Direct SER

There are several valuable alternatives to direct long-term studies in ecology (Likens 1989a). These include retrospective studies such as paleo-ecological or dendrochronological approaches (Davis 1989), space-for-time substitution studies utilizing a chronosequence approach (Pickett 1989), modeling studies utilizing physical models, such as microcosms, or computer simulation models (Shugart 1989), and experimental studies where rates are accelerated (Tilman 1989). These alternative approaches can provide powerful tools for unraveling complexity in ecosystems (Strayer et al. 1986, Franklin 1989, Likens 1989a). Combining these approaches with direct, long-term studies can provide even clearer insights toward understanding the structure, function and development of ecological systems.

Concluding Remarks. *Many of the insights referred to above were identified by correlation analysis. As such they may not be causal; even so they serve as clear indicators as to where important process or mechanistic-level studies should be done.*

Long-term trends show that short-term observations often are misleading and that decades may be required to detect significant ecological trends in complex ecosystems. SER provides data for generating hypotheses and for testing models. It provides the experience to recognize and evaluate extreme or unusual events. SER in combination with the ecosystem approach has provided many new and important insights into ecosystem function, e.g. at Hubbard Brook, estimates of ecosystem evapotranspiration, dry deposition and weathering, that are difficult to evaluate quantitatively on large, complex ecosystems. SER is a useful approach for development of ecological understanding, but to be successful studies must be sustained for long periods, during which we must learn the "... speech of hills and rivers."

(3) Air-Land-Water Linkages and Interactions

“... Time, to an atom locked in a rock, does not pass.
... An atom at large in the biota is too free
to know freedom; an atom back in the sea
has forgotten it. For every atom lost to the sea,
the prairie pulls another out of the decaying rocks.
The only certain truth is that its creatures
must suck hard, live fast, and die often, lest its losses
exceed its gains.”

Aldo Leopold
[*Odyssey* (1949)]

In the broadest view ecology brings together the talents and knowledge from geology, hydrology, meteorology, biology, and chemistry to identify complex patterns and interactions in the natural environment (see Chapter I). The goal of ecology is to clarify these patterns, linkages and interactions, and to utilize and integrate information from these diverse, but relevant disciplines toward greater ecological understanding. This, of course, is very difficult to do, but remains a goal of ecosystem ecology.

This section really is about complexity and challenges. Linkages at any scale are complex, but these are the challenges that ecologists face in trying to understand how specific, complex ecosystems are structured and how ecosystems function and interact within a global context. I will consider briefly two striking examples of air-land-water linkages and interactions, that is, the role of atmospheric deposition in the acidification of surface waters and soils, and the atmospheric deposition of toxic metals in the pollution of surface waters and soils. The new and surprising aspect provided by these examples is that a major vector for these pollutants is the atmosphere. Thus, it may be just as important, or more, to consider a lake's airshed regarding inputs of contaminants (or nutrients) as it is to evaluate the inputs from the watershed. I will conclude this section with a discussion of some of the complex linkages as water moves from the atmosphere through diverse ecosystems within a landscape.

Acid Rain

Aquatic ecosystems have diverse linkages and interactions with their airsheds and watersheds. The effects of acid rain on aquatic ecosystems provide an excellent example. Acid rain, snow, sleet and hail (atmospheric wet deposition) have been falling on increasingly widespread areas of the world during the past several decades. Large areas of North America, Europe and Asia, as well as parts of the Southern Hemisphere, now receive wet deposition that is 10 to more than 30 times more acid than would be expected for unpolluted atmospheres. Frequently, individual rainstorms or cloudwater events have pH values less than 3. In addition, dry deposition of acidic substances (gases and particles) to natural ecosystems may equal inputs from wet deposition (pp. 42 to 45). The environmental and economic consequences of acid deposition from the atmosphere have yet to be fully evaluated, but atmospheric inputs of acids and associated pollutants (e.g. toxic metals) to aquatic and terrestrial ecosystems have caused widespread alteration of natural ecosystems (e.g. Braekke 1976, Likens et al. 1979, Drabløs and Tollan 1980, Schindler et al. 1985, Schindler 1988a, Baker et al. 1991). The complexity of natural ecosystems results in a highly variable response to atmospheric pollutants in this important air-land-water linkage.

More than 90% of the emissions of sulfur and nitrogen oxides to the atmosphere in North America are anthropogenic in origin, and about 70% of the SO_2 and more than 30% of the NO_x are emitted from combustion of fossil fuels by electrical utilities and from smelters. The concentration of sulfur and nitrogen in rain and snow in eastern North America is 10 to 15 times greater than in remote areas of the globe (Galloway et al. 1984), where the average background pH is about 5.1 (Likens et al. 1987). Currently about 65% of the acidity of precipitation in the eastern US is contributed by sulfuric acid and 35% is due to nitric acid.

Air masses generally moving from west to east in the Northern Hemisphere transport air pollutants from urbanized and industrialized areas to more rural areas. Some of the sulfur and nitrogen oxides are deposited rapidly as gases or very small particles near emission sources. If the smokestack is tall enough and meteorological conditions are suitable, however, the pollutants may reside in the atmosphere from one to five days and be transported from hundreds to thousands of kilometers from the source. Within the atmosphere both SO_2 and NO_x may be converted into sulfuric and nitric acid, respectively, and then deposited on natural ecosystems in precipitation. These acids may be input directly to the surface of a lake or

may fall on the watershed of the lake and follow complex hydrologic and biogeochemic pathways to the lake (see below). For some lakes with relative small watershed areas, direct input to the lake's surface may predominate (e.g. Likens and Hendrey 1977).

As a result of political and scientific interest about the effect of acid rain on surface waters (see p. 107 ff. and pp. 127 to 135), many lakes in the United States were studied extensively during 1980–1990. Lakes of the Adirondack Mt. region in New York State were of particular interest because of the high loading of acid substances from the atmosphere, and the presumed susceptibility of the lakes and soils in this area to these airborne pollutants.

The diversity of lakes in this remote, mountainous region is enormous. Clearly, there are many complexities involved. Lakes have different sizes, depths, ratios of surface area to watershed area, chemical contents and biological components. They may occur at different elevations, and have different vegetation and flow paths of water within the drainage area. A scheme, largely based on hydrologic flow paths, was established to classify the lakes in the Adirondack Mt. region into important “types” (Fig. 31). The direct and implied linkages between geology, hydrology and chemistry are clear in this scheme. As part of the US Environmental Protection Agency's Eastern Lake Survey, a total of 155 lakes was sampled to characterize the total population of 1290 lakes that were >4 ha in size within the Adirondack Mt. region (e.g. Brakke et al. 1988, Landers et al. 1988). Some 83% of these lakes, plus 49 special interest lakes, were located in the Adirondack Park (Fig. 32; Driscoll et al. 1991). The large amount of data and diversity of lakes provided an opportunity to develop some generalizations based on correlation analysis.

Some 14% of the lakes >4 ha in area were acidic (acid neutralizing capacity, ANC, $\leq 0 \mu\text{eq liter}^{-1}$). Another study (Kretser et al. 1989) based on lakes larger than 0.5 ha found that 26% of the lakes in the Adirondack Mt. region were acidic. These lakes generally were located in the western and southern areas of the Park where many lakes are located at high elevation (>600 m) and have drainage basins with shallow glacial till (Driscoll et al. 1991). Most of the lakes in the area were classified as drainage lakes (Fig. 32). The flow path of water seemed to be an important determinant of ANC in these lakes (Fig. 31).

Based on other studies of the lakes in this region, regarding chemical changes (e.g. Schofield 1976, Kramer et al. 1986, Asbury et al. 1989), regarding changes in fish populations (e.g. Schofield 1976, 1980, 1982, Schofield and Trojnar 1980) and regarding the paleoecological record in

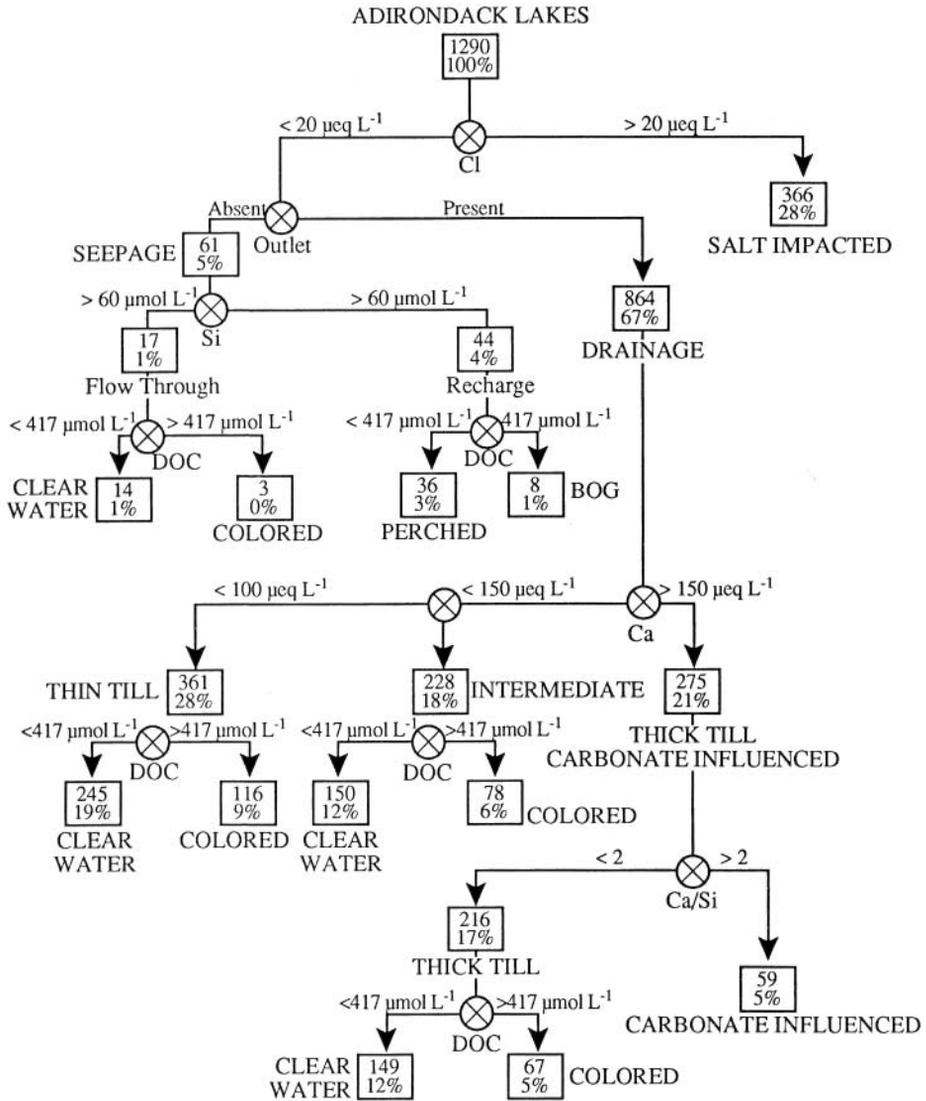


Fig. 31. Scheme for classifying lakes in the Adirondack Mt. region of New York State, USA. Number and percentage of lakes (in boxes) refer to the Eastern Lake Survey-I of lakes >4 ha in surface area. (From Driscoll et al. 1991; modified)

lake sediments (Charles 1985, Driscoll et al. 1991), it can be concluded that the major chemical and biological changes observed in these lakes were caused by increased atmospheric deposition of pollutants, primarily sulfuric acid, during the past few decades. This increased deposition of acid

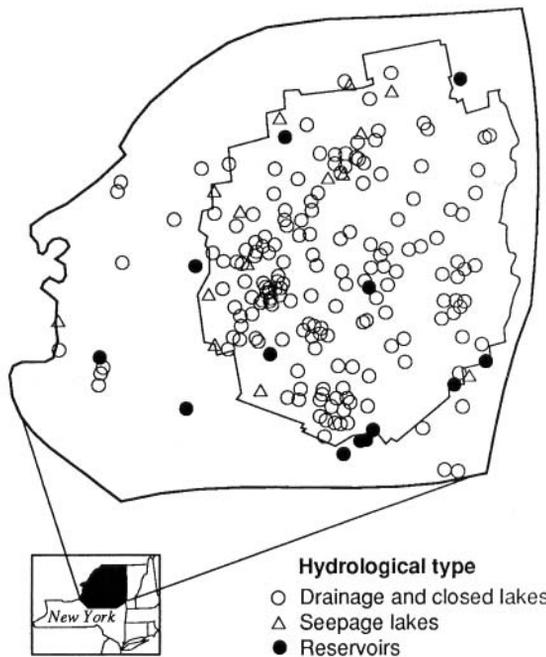


Fig. 32. Location of lakes of different hydrologic type within the Adirondack Mt. region of New York State, USA. Data were collected as part of the Eastern Lake Survey and special interest lakes. Inner line indicates the boundary for the Adirondack Park. (From Driscoll et al. 1991; modified)

pollutants in turn is linked with increased emissions of SO_2 and NO_x from the combustion of fossil fuels in recent decades (e.g. Likens et al. 1972, Likens and Bormann 1974, Butler and Likens 1991; see also p. 105 ff. and p. 130 ff.). In Norway (Henriksen et al. 1988), in Sweden (Almer et al. 1974), and in Finland (Kämäri et al. 1991), long-term studies of the air-land-water interactions have led to similar conclusions about the recent acidification of surface waters from atmospheric deposition.

The linkage between atmospheric emissions, the deposition of acids and ecological effects of these acids on terrestrial and aquatic ecosystems has been the focus of intense research and political debate during the past two decades. There are, however, many other air-land-water interactions that have not been identified clearly, let alone studied adequately (Likens 1985a). For example, it is well known that nitric acid is a major component of acid rain, but most attention, relative to effects and management, has been directed toward understanding the biogeochemistry of sulfur. More-

over, little or no attention has been given to linkages with the biogeochemical cycles of carbon and base cations. The linkage between atmospheric NO_x (the precursor of nitric acid in acid rain) and volatile organic compounds (VOC's) is crucial for the production of atmospheric ozone (e.g. National Academy of Sciences 1992). Currently there is a major effort in the US and elsewhere to plant trees in urban centers in an attempt to slow the rate of accumulation of CO_2 in the atmosphere through biotic uptake, and thereby reduce global warming. What is the linkage between this effort, which also will increase emissions of VOC's in urban areas, and separate efforts to reduce NO_x emissions in an attempt to control ozone production in these areas? Clearly, research and management decisions related to these different environmental problems should be integrated, as well as consider the interactions between the various air-land-water linkages.

Toxic Metals

Mercury

The occurrence of mercury in fish in lakes remote from industrial activity has pointed clearly to a need to understanding the air-land-water linkages for natural ecosystems. Concentrations of mercury in fish, high enough to warrant warnings about human consumption, have been found recently in widespread areas of the United States, Canada and Scandinavia (e.g. Schneider 1991). Fish tissue containing >0.5 and $>1.0 \mu\text{g total Hg g}^{-1}$ wet weight is considered unsuitable for human consumption in Canada, and the USA and Sweden, respectively (Lindberg et al. 1987). Most ($>80\%$) of this mercury exists as methylmercury (Lindberg et al. 1987, Grieb et al. 1990). Because of biomagnification through the food web, larger fish usually contain higher concentrations of total mercury in their tissues.

Globally, the magnitude of natural emissions of mercury to the atmosphere has a large uncertainty, but is believed to exceed anthropogenic emissions by a factor of about 3 to 4:1 (Lindberg et al. 1987), even though anthropogenic emissions of total mercury have increased two- to three-fold between 1900 and 1970 (Andren and Nriagu 1979). The primary sources of anthropogenic emissions of mercury to the atmosphere are thought to be from combustion of coal, from mining and smelters, from industrial processes in the production of chlorine and caustic soda, and from municipal incinerators (Pacyna 1987). Although it appears that long-range atmospheric transport to airsheds and watersheds of lakes is a major source of

anthropogenic mercury (e.g. Fitzgerald and Watras 1989, Grieb et al. 1990, Watras et al. 1991), it is the linkage with other biogeochemical cycles that determines its availability to organisms within a lake.

The availability of mercury to organisms depends primarily on whether it is methylated or not. Conversion from the elemental form to methylmercury (the most toxic form) is done primarily by bacteria, but chemical methylation also is possible (Lindberg et al. 1987). Methylation occurs primarily in the sediments of lakes and the rate depends on pH, redox potential, concentration of organic substances, temperature and the presence of methylating bacteria. Thus, the linkage with other biogeochemical cycles is clear.

Consider, for example, the air-land-water linkages between acid rain and mercury. Increased combustion of fossil fuels, primarily coal, simultaneously adds more mercury and acid-forming substances to the atmosphere. As these fall to land and water surfaces by wet and dry deposition additional linkages are forged. For example, elemental mercury can be mobilized from the terrestrial watershed by increased acidification of soils, and although there are some conflicting data, generally it has been found that bacterial methylation in lakes is enhanced at lower pH values (e.g. Lindberg et al. 1987, Grieb et al. 1990, Bloom et al. 1991, Watras et al. 1991). Thus, fish in acidified lakes normally contain more mercury in their tissues than fish in more alkaline lakes.

Mercury is highly toxic to organisms, and is the "only metal which indisputably biomagnifies through the food chain" (Lindberg et al. 1987). This new air-land-water linkage renews attention on the human hazard from mercury, which has been known to be toxic since the writings of Pliny (Schneider 1991).

Many important answers remain to be found. For example, how widespread is the problem? What factors regulate atmospheric deposition of mercury? What are the primary controls on methylation in lakes? Some 25 years ago mercury pollution emerged as a problem from specific industrial point sources. Now, however, mercury pollution, through the air-land-water linkage, has all the ingredients to become one of the major environmental problems of the 1990's.

Lead

A similar pattern of air-land-water linkages is found for lead (see also p. 38 ff.). Although problems exist in comparing historical estimates of atmo-

spheric deposition based on different sampling procedures, relatively large amounts of lead have been added to the Laurentian Great Lakes and their watersheds from atmospheric deposition in recent decades (e.g. Arimoto 1989, Gatz et al. 1989). It is surprising that atmospheric inputs of lead could be important for such immense lakes, particularly considering their large drainage basins and the major amount of human activity within these basins. Nevertheless, despite some uncertainties in the data, it is clear that atmospheric deposition is the dominant source for a variety of toxic organic and inorganic chemicals for these large lakes (Arimoto 1989, Kelly et al. 1991).

Hydrologic Linkages

Lakes and streams, like other ecosystems, have linkages to adjacent and distant ecosystems by a variety of inputs and outputs. The vectors for these inputs and outputs may be either meteorologic, hydrologic or biologic (Likens and Bormann 1972). For example, precipitation falling on hilly or mountainous terrain ultimately is moved downslope by gravity, but water may follow complex routes. Water can follow many pathways to a lake, for example, as overland flow, through the upper nonsaturated zone, as ground water, or as direct precipitation (Fig. 33). This movement, however, can be

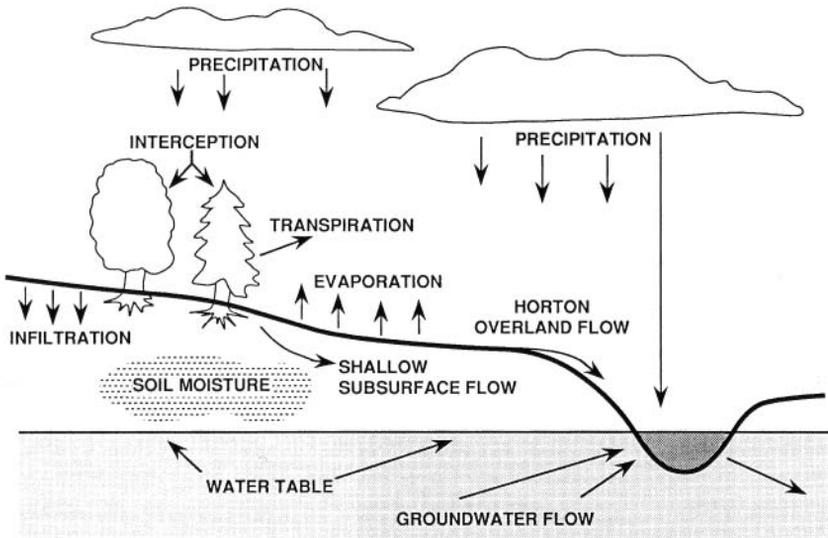


Fig. 33. Major aspects of the hydrologic cycle for ecosystems in mountainous terrain

viewed from various perspectives. From a hydrological point of view the questions focus on mechanisms of water transport to a stream or to a lake. Geologists may be interested in the chemical reactions that occur as water flows along these various routes. Biologists examine air-land-water linkages somewhat differently. They tend to focus on the availability of water and nutrients for plants, animals and microorganisms, species adaptations to wet and dry habitats, and community organization within these different habitats.

Stream ecosystems

Overland flow of water within stream or river channels is an obvious path for water movement downhill, but streams also are functioning ecosystems (e.g. Cummins 1974, Likens 1984). Both biotic and abiotic processes within the stream itself can affect dramatically what is moved downstream. Numerous studies done at Hubbard Brook (e.g. Meyer and Likens 1979, Hall et al. 1980, Meyer et al. 1981, McDowell 1985) and elsewhere (e.g. DeAngelis et al. 1990) clearly show the role of this flowing water ecosystem in altering the quantity, quality and timing of transport of material downstream. For example, within the Hubbard Brook Experimental Forest, experiments involving the addition of sulfuric acid, hydrochloric acid, dissolved organic substances, aluminum salts, nitrogen compounds, and phosphorus have been done in headwater streams (Meyer 1979, Sloane 1979, Hall et al. 1980, 1985, McDowell 1982). In all cases the increased concentrations of chemicals from the experimental additions had disappeared within 30 to 400 m downstream. These changes downstream were not due simply to dilution, but were the result of instream processes. These results illustrate some of the functions of the stream ecosystem, but complicate attempts to understand linkages in a quantitative way. For example, what is the fate of materials added to the stream ecosystem? What is the quantitative spatial and temporal response of trees or microbes, for example, to changing hydrologic and biogeochemic conditions in streams? How are chemical quality and quantity of stream water regulated? Answers to such questions are important for evaluating air-land-water linkages and interactions.

By and large, the chemistry of stream water at Hubbard Brook is very different from the chemistry of precipitation (e.g. Likens et al. 1977, 1985a). Even so, the functions of terrestrial and associated aquatic (e.g. stream) ecosystems are very effective at regulating the concentration of

dissolved substances in stream water within relatively narrow ranges. Concentrations of dissolved substances can vary with discharge (e.g. Johnson et al. 1969, Lawrence and Driscoll 1990), but the variations are small compared to the large daily, seasonal or annual fluctuations in the volume of streamflow (Fig. 34). Thus, outputs of dissolved substances are highly predictable based on annual streamflow alone (Likens et al. 1977, 1985a). In contrast, concentrations of particulate matter vary exponentially with discharge. This linkage represents one of the major findings of the HBES.

Both biotic and abiotic components of the ecosystem regulate stream-water chemistry. For example, living vegetation provides an important regulating component through transpiration of water vapor. As a result of transpiration, nutrient elements are conserved within the ecosystem because less liquid water is available to transport dissolved substances and particulate matter from the ecosystem in drainage waters. This represents a reverse twist on the air-land-water linkage.

Surprisingly, even the dissolved organic carbon (DOC) concentration in headwater streams at Hubbard Brook is relatively constant at about

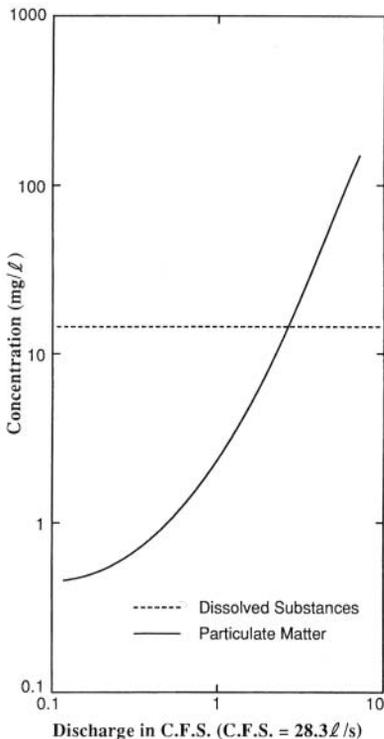


Fig. 34. General relationship between concentration of dissolved substances and particulate matter, and streamflow in the Hubbard Brook Experimental Forest. (From Bormann et al. 1969; modified)

2 mgC liter⁻¹, irrespective of changes in elevation or volume of streamflow (Johnson et al. 1981, McDowell and Likens 1988). How is this concentration regulated so tightly? It is informative to follow the changes in DOC concentrations throughout the entire system (Fig. 35). Dissolved organic carbon in ambient precipitation has a concentration of about 1 mgC liter⁻¹; after passing through the forest canopy (throughfall), the concentration increases to about 10 mgC liter⁻¹. Below the humus-rich forest floor, DOC concentration increases to about 30 mgC liter⁻¹ and to about 90 mgC liter⁻¹ in the surface soil horizons. Then, the concentration of DOC in the soil solution decreases sharply in the deeper parts of the soil profile to about 2 to 3 mgC liter⁻¹ (Fig. 35). This concentration (2 to 3 mg liter⁻¹) in soil solutions in the deeper mineral soils is about the same concentration as in stream water. Also, large seasonal variations in DOC concentrations were observed in water of the upper soil horizons, but variations were small below the B-horizon and in stream water (McDowell and Wood 1984). These data suggest that co-precipitation of iron and/or aluminum with DOC

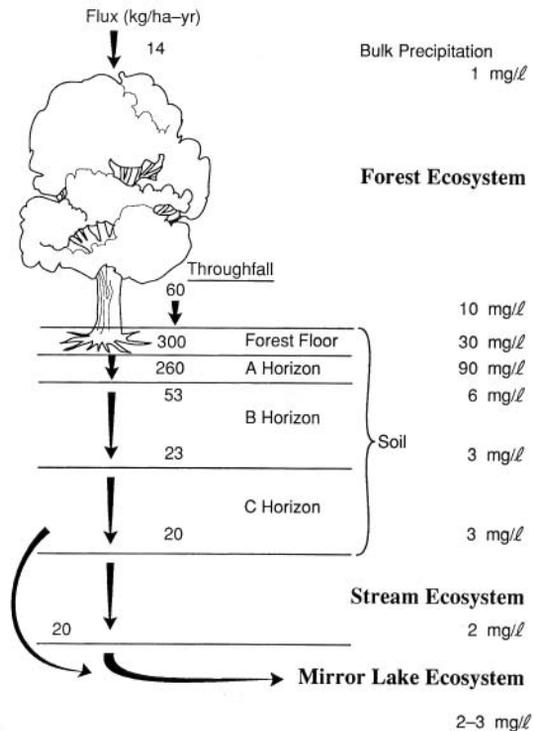


Fig. 35. Flux of dissolved organic carbon through forest and aquatic ecosystems in the Hubbard Brook Valley. (From McDowell 1982; modified)

on sesquioxides of the B-horizon of the soil are largely responsible for regulating streamwater concentrations (McDowell and Wood 1984). Most of the drainage water would need to pass through the entire soil profile most of the time in order for the stream concentration to be regulated so tightly. Is this realistic?

At Hubbard Brook the location of stream-gauging weirs was established to measure all of the water draining from a watershed-ecosystem. A weir was constructed on each catchment at some point where the bedrock was close to the surface and where the weir could be attached to the bedrock. Thus, all of the drainage water was forced to flow through the weir as streamflow (Likens et al. 1977). Such placement allows for quantitative measurements of drainage water from the catchment. At Hubbard Brook, streamflow is measured continuously, throughout the year. In order to characterize the biogeochemistry of an ecosystem or of a larger landscape, however, where is the correct location for such weirs? It was found that for a variety of chemicals, e.g. nitrate and pH, that there is a large change in concentration elevationally along the course of the stream (Fig. 36). Although the catchments at Hubbard Brook are relatively homogeneous in terms of physical characteristics (Likens et al. 1977), there are changes in vegetation, soils and hydrologic flowpaths with elevation, and the chemistry of stream water can reflect these changes. The location of sampling stations becomes a particularly important consideration when attempting to establish a long-term, monitoring network, such as the US Environmental Protection Agency's current Environmental Monitoring and Assessment Program (EMAP). Obvious complications can result when attempting to compare the biogeochemistry of spatially diverse ecosystems (see p. 19 ff.). This elevational aspect will be discussed in more detail below.

A tightly regulated annual pattern also was found for hydrogen ion concentrations in stream water at the weir of Watershed 6 of the HBEF (Fig. 37). Even though precipitation has markedly different concentrations of hydrogen ion during summer and winter (Fig. 13), the concentration in stream water varies little throughout the year. This chemistry is being tightly regulated by the land-water linkage. The pattern is more complex, however, from a larger, spatial perspective. Although streamwater concentration of hydrogen ion is being regulated temporally, there are marked differences along an elevational gradient (Fig. 36; Johnson et al. 1981, Lawrence et al. 1986, Lawrence and Driscoll 1990). Concentrations of hydrogen ion at the highest elevations (>800 m) in Falls Brook of the HBEF (Fig. 4) may be an order of magnitude higher than concentrations

400 m lower in the watershed (Fig. 36). This spatial variability may change seasonally as well (e.g. Johnson et al. 1981).

How then does this regulation occur? Is the drainage water following consistent flowpaths, or even subsurface channels, commonly called macropores or “pipes”? Macropores may be formed in soil in many ways, e.g. cracks along boulders or rocks, living or dead root channels, worm burrows, etc. (Fig. 38). In a recent study done by Stresky (1991) in soils at Hubbard Brook, macropores were found to be rather common, and

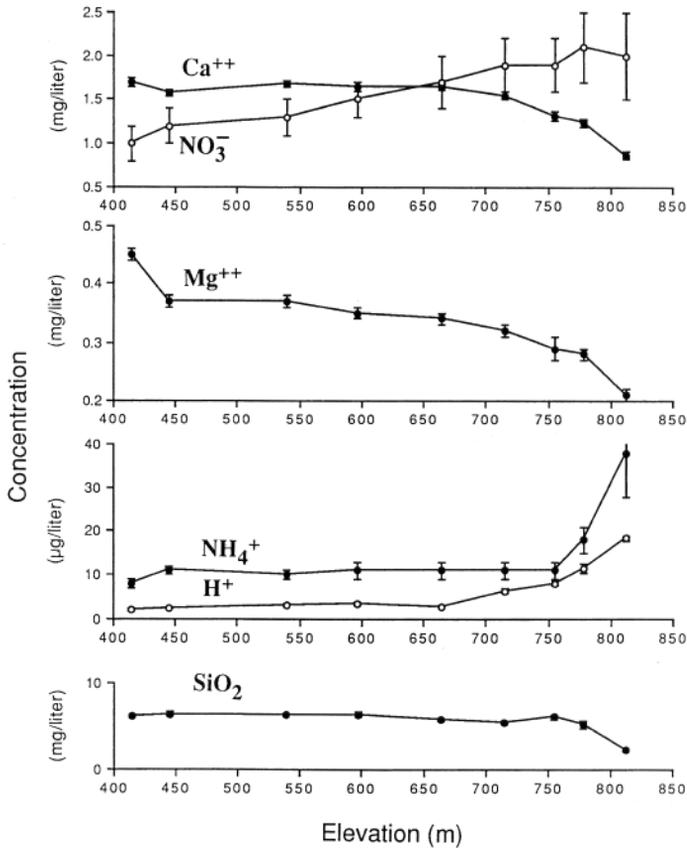


Fig. 36. Mean stream chemistry for Falls Brook of the Hubbard Brook Experimental Forest during February 1975 through February 1978 at different elevations along the course of the stream. Sampling site at 812 m is a first-order stream; from 778 to 715 m is second-order; 664 to 597 m is third-order; 539 to 445 m is fourth-order; and 415 m is fifth-order. Vertical bars are \pm one standard deviation of the mean. (From Johnson et al. 1981; modified)

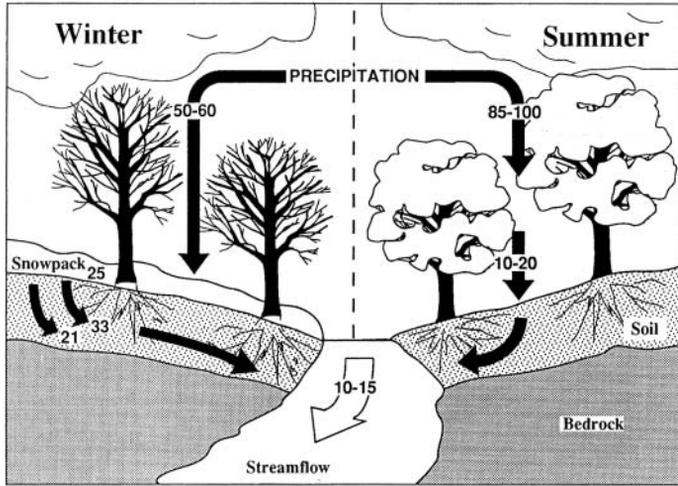


Fig. 37. General relationships for H-ion concentrations ($\mu\text{eq liter}^{-1}$) during summer and winter seasons at the Hubbard Brook Experimental Forest. (From Hornbeck et al. 1976; modified)

frequently intersected, but comprised only about 0.2% of the area of the soil profiles examined (Table 8). The role of macropore flow in determining streamwater chemistry is an important topic for research at Hubbard Brook.

Knowledge about how water actually flows through an ecosystem is very important for developing an ecological or biogeochemical understanding. Most hydrologic models assume a homogeneous soil matrix and little biotic influence other than transpiration (e.g. Cosby et al. 1985). For example, stemflow is very important hydrologically or biologically for some forest ecosystems. Thus, Glatzel et al. (1986) found that stemflow in a beech (*Fagus sylvatica*) forest in Austria had a major effect on the soil chemistry several meters downhill from the base of tree stems, as well as on forest

Table 8. "Pipes" or macropores in soils of the White Mountains, New Hampshire, USA. (From Stresky 1991)

59 soil faces (75 m²) examined; 287 pipes (0.18 % of area examined)

Average pipe:

2.5 cm in diameter (range = 0.5 to 7.5 cm)

16 cm depth (range = 2 to 130 cm)



Fig. 38. Outline of various macropores in the soil of the White Mountain National Forest, New Hampshire. (Photos: S. Stresky and G. E. Likens)

floor vegetation. Also in forest ecosystems where stemflow is a major pathway for precipitation water to move through the forest canopy, the probability for this stemflow water to flow along or in root channels at the base of trees may be high. No current hillslope model incorporates stemflow or macropore flow in a quantitative way (C. A. Federer,

pers. comm.). Obviously, soils are very heterogeneous and macropore flow contributes to this complexity with regard to developing understanding. Although a major challenge, it is encouraging to see research and modeling efforts now attempting to unravel this complexity (McDonnell 1990).

The flow path of water through terrestrial catchments has been proposed or shown to affect solute chemistry in significant ways (Johnson et al. 1969, 1981, Likens 1984). For example, deeper flowpaths through the soil may result in higher concentrations of base cations, nitrate or alkalinity in drainage waters (e.g. Chen et al. 1984, Peters and Driscoll 1987, Lawrence et al. 1988, Lawrence and Driscoll 1990, Mulholland et al. 1990). Studies in New Zealand hillslopes (McDonnell 1990) suggest that stored ("old") soil water may be transported downslope in macropores to first-order stream channels during relatively large rainstorms. Studies on hillslopes in Tennessee, USA, suggest that macropores are important physical conduits for water, but have little effect on water quality (Luxmoore et al. 1990).

In studies at Hubbard Brook, concentrations of H^+ and DOC tend to be highest in soil water draining the forest floor, whereas inorganic Al^{n+} and dissolved silica concentrations tend to be highest in soil water draining the lower mineral horizons (B_s) (Johnson et al. 1981, Lawrence et al. 1988, McDowell and Likens 1988, Lawrence and Driscoll 1990). During very wet periods, such as spring snowmelt, when the zone of soil saturation moves upward, it might be expected that streamwater concentrations of H^+ and DOC would increase and inorganic aluminum would decrease because of expected increases in lateral flow through the upper portions of the soil profile. In fact, the data suggest that the relationships determining streamwater chemistry are much more complicated as changes in lateral flow paths provide only a superficial explanation for the spatial and temporal patterns observed. Lawrence and Driscoll (1990) have suggested that a combination of factors are involved, including: (1) spatial variability in soil type and depth and vegetation type (Lawrence et al. 1986), (2) modification of soil profiles adjacent to stream channels because of lateral flow patterns, and (3) effects of macropore flow. To this list must be added in-stream effects, that is, the effect of activities within the stream ecosystem that result in changes in stream chemistry.

Dissolved and particulate materials entering a stream are transformed, stored or transported by a variety of physical, chemical, hydrological and biological processes within the stream ecosystem (Fisher and Likens 1973, Sedell et al. 1973, Boling et al. 1975, Meyer and Likens 1979, Meyer et al.

1981, McDowell and Likens 1988). Whereas organic carbon and nitrogen are processed primarily by biological activity within Bear Brook, geochemical transformations seem to predominate for phosphorus (Meyer 1979, Meyer et al. 1981). These ecosystem-level functions also produce temporal and spatial patterns in the flux of these nutrients from the stream ecosystem. As an example, the flux of phosphorus in the Bear Brook ecosystem (Fig. 4) within the Hubbard Brook Experimental Forest can be used to illustrate some of these linkages.

The amount of precipitation and streamflow can fluctuate widely from day to day, from week to week or from year to year in the Bear Brook watershed-ecosystem. The flux of phosphorus is related to these fluctuations. The daily net balance of total phosphorus in Bear Brook during water-year 1974–75 is shown in Fig. 39. During this year there was a net loss of 0.5 kg phosphorus, largely accounted for during peak discharges in March 1975. There also was tremendous temporal variability, but most of this variability was due to variability in streamflow, because phosphorus was exported primarily (78%) in particulate matter (Meyer and Likens 1979), and particulate matter export was exponentially related to streamflow (Fig. 34).

Stream ecosystems have a finite capacity to store or release nutrients such as phosphorus, and this capacity is apparent from a longer time-scale (Fig. 40). During the 13 years shown in Fig. 40, inputs of phosphorus totaled about 131 kg and outputs were 152 kg, producing a long-term net

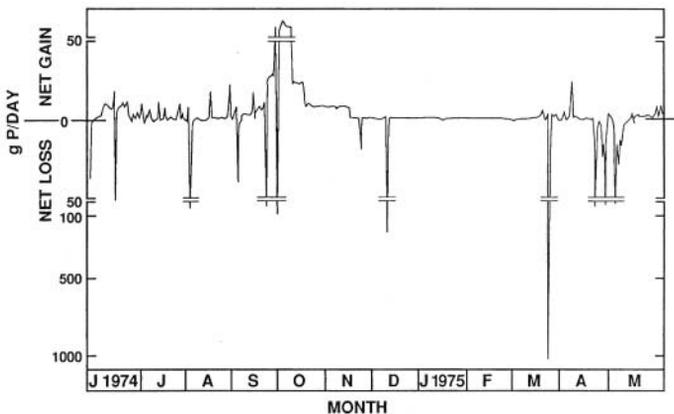


Fig. 39. The daily net flux of total phosphorus in Bear Brook during 1974–75. Values greater than zero indicate net gain; values less than zero indicate net loss for the stream ecosystem. Note change in scale on the ordinate. (From Meyer and Likens 1979)

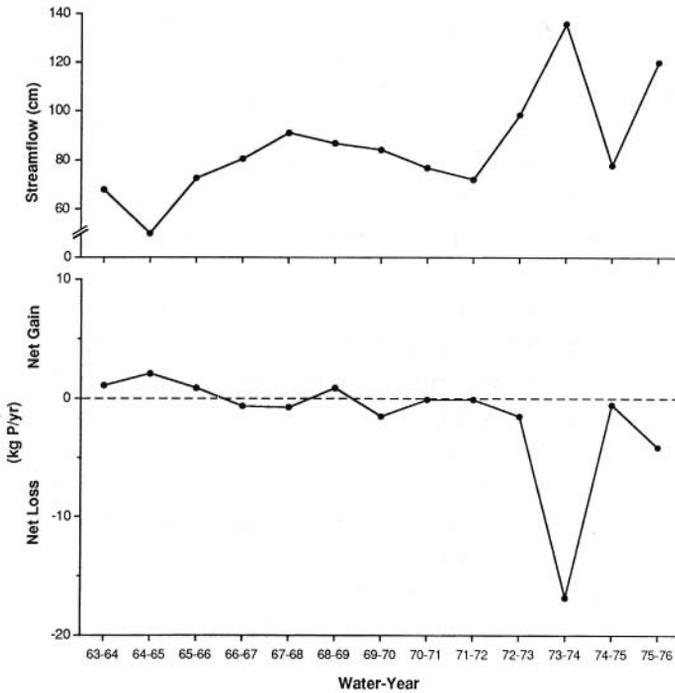


Fig. 40. Net annual flux of phosphorus for Bear Brook of the Hubbard Brook Experimental Forest from 1963 to 1976. (Data on phosphorus provided by J. L. Meyer)

export from Bear Brook of 21 kg. On a watershed basis this value represented on average a net export of 0.01 kg P/ha-yr. During this 13-yr period, four years had net gains of phosphorus in the stream ecosystem and nine had net losses. The annual net export during a wet year (1973–74) was 0.13 kg P ha⁻¹ or 16-fold greater than that during a dry year (1964–65). In 1968–69 an annual streamflow of about 87 cm resulted in a net gain of phosphorus, whereas an annual streamflow of about 78 cm in 1974–75 resulted in a net loss (Fig. 40). These data point strongly to the variability caused by short-term, peak discharges (Likens 1984) during the annual cycle. Even though materials may be stored temporarily in the stream ecosystem, these materials are actively being altered by biological, chemical and mechanical action (Table 9). These are important linkages with downstream ecosystems.

The combined effects of all of these factors and linkages within watersheds and associated aquatic ecosystems produce the complicated spatial and temporal patterns of streamwater chemistry observed at Hubbard Brook. And it could be argued (e.g. Likens et al. 1977) that the HBEF is a relatively simple and homogeneous system!

Table 9. Ratios between outputs (O) and inputs (I) for annual fluxes of organic carbon, nitrogen and phosphorus in Bear Brook, USA. (From Meyer et al. 1981)

Fraction	Organic carbon O/I	Nitrogen O/I	Phosphorus O/I
Gaseous	250	?	—
Dissolved	1.0	1.0	0.74
Fine particulate	2.1	1.6	2.0
Coarse particulate	0.29	0.22	0.54

Riparian zone linkages

A subdiscipline has developed during the last two decades around the ecosystem concepts relating to the riparian zone, that is, the interface between the stream ecosystem and the adjacent terrestrial ecosystem. Studies focus on the biotic-abiotic interactions along the banks and flooding-zones of streams and rivers (Gregory et al. 1991). Cummins identified some of these linkages in an informative diagram of the riparian zone in 1986. I have modified this conceptual diagram by adding hydrologic components such as precipitation, ground water and so forth, as well as additional biotic and geologic components to provide a more complete ecosystem framework for the air-land-water linkages of the riparian zone (Fig. 41). For example, trees obviously have roots, even though they frequently are ignored in studies of the riparian zone. These roots penetrate into the sediment, either into the stream sediment itself or into the soil adjacent to the stream. Roots stabilize the stream channel, take up nutrients and water and provide food and shelter for organisms. In addition to annual inputs of leaves and other litter, which may be a major input of organic matter for small streams (e.g. Fisher and Likens 1973), trees eventually die. As a result, the above-ground parts may fall into the stream and produce organic debris dams, hydrologic macropores may form when the roots decay, the dead organic matter may provide energy sources for stream organisms, and so forth. These are important components of the structure, function and development of a dynamic riparian zone, but the evaluation and integration of these components may be a matter of perspective and focus. Often neither the hydrologist, geochemist nor the biologist keeps all of these components and their linkages in mind when addressing research questions or attempting integration. Take, for example, the biologist who may be studying the factors

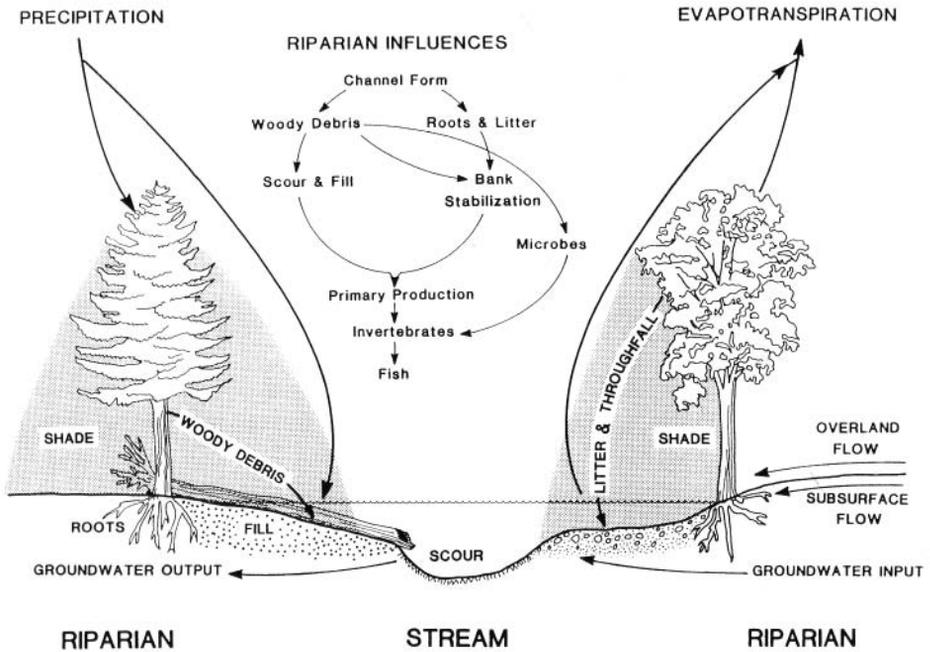


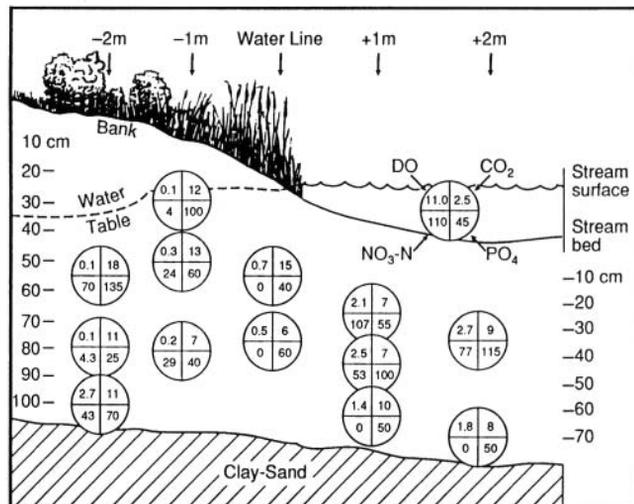
Fig. 41. Conceptual diagram of the riparian zone for streams and rivers. (From Cummins 1986; modified)

controlling the rate of aquatic primary production, or what eats the primary production of the stream ecosystem, but may not be interested in (or aware of) the fact that tree litter, including large woody debris, and roots are important in regulating bank or sediment stabilization (e.g. Bormann et al. 1969, Bilby and Likens 1980, Bilby 1981) and patterns of habitat diversity and metabolism (e.g. see Hedin 1990). At the same time this organic matter may be broken down by microbes and/or mechanical forces (e.g. current), thereby affecting the hydrology, chemistry and biology downstream. The riparian zone may act as a nutrient sink for dissolved nutrients moving in soil water from the watershed to the stream (e.g. Lowrance et al. 1984). It needs to be stated again that streams and their riparian zones do not function in these linkages like Teflon troughs.

Another group of biologists is interested in another part of this system, the so-called hyporheic zone (Orghidan 1959). The hyporheic zone has been defined as, "in running water this habitat . . . represents the interstices that are formed in the mixture of coarse sand, gravel and rocks typically found in the rithron region of streams" (Williams 1984). Probably few sci-

entists would understand this definition! The hyporheic zone is an intermediate zone between the stream water and the ground water below, that is characterized by an intermediate flow rate of water (but fluctuating in time and space), variable and fluctuating chemistry (Fig. 42) and a characteristic group of animals. The animals that live in the interstices between pebbles and sand grains in this moving water below streams are quite interesting ecologically, but poorly known. Indeed, large numbers of individuals, and often new and fascinating species are being found in this zone. In some locations hyporheic animals are found up to 2 km from the river channel (e.g. Stanford and Ward 1988). Unfortunately, the hyporheic zone is being defined currently only on the basis of the *animals* that are found there. The hyporheic zone is an exciting area for study from an animal ecologist's point of view, but what is the relationship between the hyporheic zone and the riparian zone, or the watershed-ecosystem or the airshed? What is the relationship between the roots that penetrate into the riparian zone and the animals and microorganisms in the hyporheic zone? In fact, the water flowing through old root channels (macropores) as "pipe flow" may be affecting the distribution of chemicals, particularly dissolved organic matter, and thus, affecting hyporheic animals in ecologically significant ways. Specific animals and microbes probably are responding to organic matter that was produced in the riparian zone by specific plant species (e.g. Cummins and Klug 1979, Rounick and Winterbourne 1983, Leff and McArthur 1990, Richardson 1990) and vice versa, representing ecologically important linkages and interactions.

Fig. 42. Spatial variability in concentrations of dissolved oxygen (DO in ppm), carbon dioxide (CO_2 in ppm), $\text{NO}_3\text{-N}$ in $\mu\text{g liter}^{-1}$ at various depths in, and adjacent to, the hyporheic zone of Duffin Creek, Ontario. (From Williams 1984)



Organic debris dams

Our research at Hubbard Brook has shown that organic debris dams are common in streams in forested regions of the northeastern US (Table 10) and are important in regulating storage and transport of inorganic and organic matter in streams (Bilby and Likens 1980, Bilby 1981, Likens and Bilby 1982). In addition, metabolic rates are elevated in organic debris dams, making them "hot spots" of biological activity in streams (Hedin 1990).

Organic debris dams were experimentally removed from 175 m of a second-order stream at Hubbard Brook. As a result, the annual export of dissolved substances increased by 6% and particulate matter increased by 530% (Bilby 1981). The more important result in terms of linkages, however, was that with organic debris dams intact the long-term average export of dissolved substances exceeded particulate matter exports by about 5 to 1 (Likens et al. 1977), whereas after the organic debris dams had been removed this pattern was reversed and particulate matter exports exceeded export of dissolved substances by 2 to 1 (Bilby 1981).

We currently are studying the effects of watershed disturbance (e.g. clearcutting) on the formation and maintenance of organic debris dams during long periods (Hedin et al. 1988). Interestingly, organic debris dams have disappeared and sediments have become mainly inorganic in a small

Table 10. Distribution of organic debris dams, organic matter and proportion of the total standing stock of organic matter contained in organic debris dams in first-, second- and third-order streams of the Hubbard Brook Experimental Forest. (From Bilby et al. 1980)

	Stream-order		
	First	Second	Third
Number of dams per 100 m of streambed	33.5	13.7	2.5
Organic matter per m ² of streambed (kg)	3.52	2.58	1.64
% of total organic matter contained in dams	74.5	58.4	20.0
% of streambed area covered by dams	8.1	4.9	1.2

headwater stream following experimental deforestation of its catchment in 1965. These results suggest that disturbance such as deforestation can affect the dynamics of organic debris dams and thus stream ecosystems for 80 years or more (Fig. 43; Likens and Bilby 1982, Hedin et al. 1988).

Long-term degradation and accretion of sediments in streams also is related to the presence of organic debris dams (Fig. 43). When trees in a

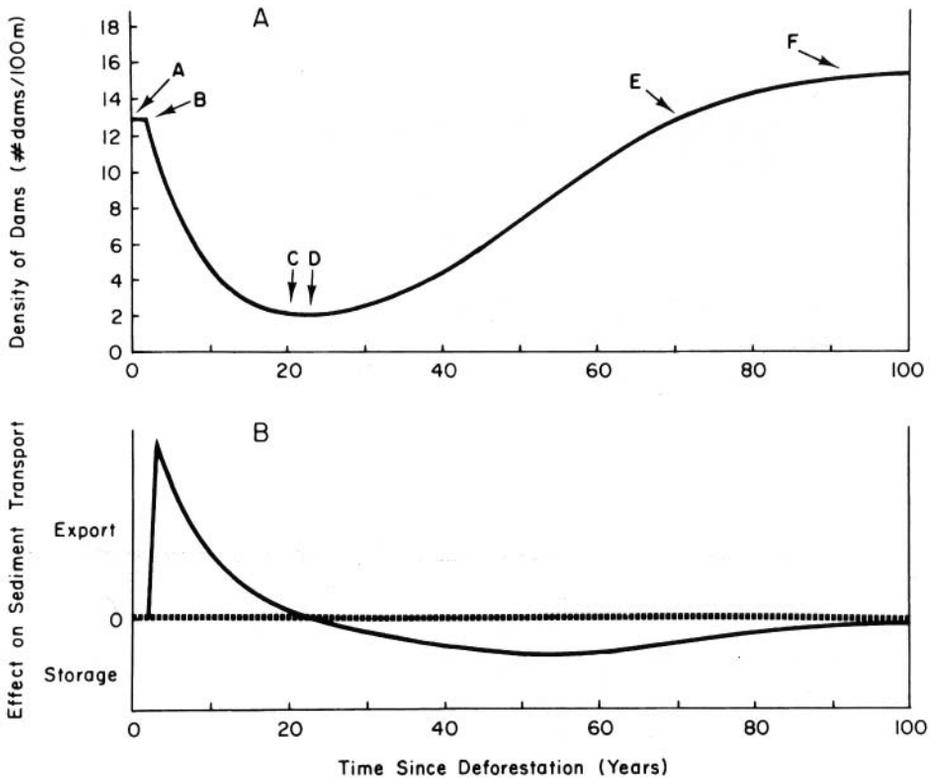


Fig. 43. (A) Model describing how density of organic debris dams changes as a function of time since deforestation in low-order streams of the Hubbard Brook Experimental Forest. A to F: locations where the model has been constrained based on empirical data (Hedin et al. 1988). Initial density of dams (at time = 0) is assumed to be representative of a 70-yr-old, second-growth hardwood forest in New England. (B) Effect of changes in abundance of organic debris dams, predicted by model A on the transport of sediment. Positive values represent additions of sediment to stream transport; negative values, removal of sediment from stream transport. (From Hedin et al. 1988)

catchment are felled, blow down or otherwise naturally fall down there must be time for trees adjacent to the stream to grow large enough to form new or replacement dams. To form a dam a tree that falls across the stream must have adequate length and mass to form a barrier across the channel. Twigs do not form a persistent dam in a channel of any size. Characteristics of tree species including growth rate, tensile strength, length and shape of bole, etc. determine the time required to form new organic debris dams following major disturbance (Likens and Bilby 1982). Past cutting practices in the White Mountain National Forest, USA, where larger trees were selectively removed, probably reduced the number of organic debris dams on larger fifth- and sixth-order streams. Thus, it is the biological characteristics of the catchment, as well as management history, that determines the long return interval for organic debris dams following disturbance (Likens and Bilby 1982); and it is the organic debris dams that influence the linkage of hydrologic transport of sediment downstream.

In systems with little overland flow, e.g. forest ecosystems, sediment input to lakes is primarily from erosion within the stream channel rather than from some general erosion of large areas of the catchment (Likens 1984). Thus, organic debris dams can play a central role in regulating this linkage to downstream systems, such as lakes.

Lake ecosystems

Some lakes apparently receive most of their water from surface drainage, others from subsurface seepage. Several studies now have shown that seepage water can move into a lake or out of a lake (Born et al. 1979, Vanek 1987, Winter 1990, and review in Asbury 1990). This seepage may be of large quantity and variable quality. The complexity of this hydrologic linkage with lakes is illustrated clearly in Fig. 44, which shows the potential flow paths for ground water in a multiple-lake system containing aquifers. This type of system could be relatively common in lake districts. These linkages between ground water and lakes are probably the least understood component of the hydrology of lakes (e.g. Winter 1976, 1985).

We have undertaken a comprehensive study of the hydrologic budget of Mirror Lake within the Hubbard Brook Valley (Winter 1985, Winter et al. 1989, Asbury 1990). Because this lake has three inlet tributaries and an outlet, it typically would be characterized as a drainage-type lake. Our results show, however, that groundwater seepage through the sediments is

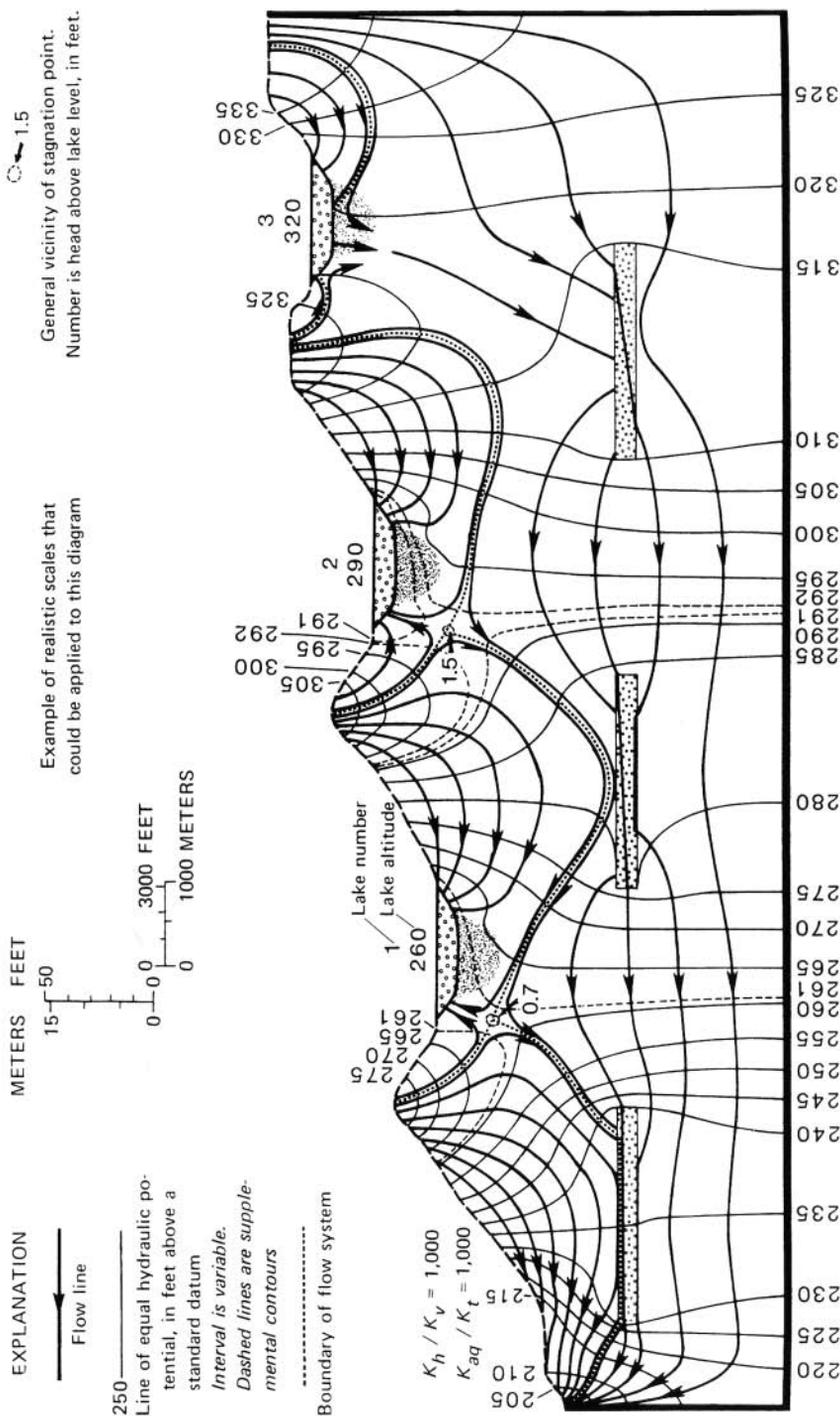


Fig. 44. Hydrologic section of quasi-quantitative net flow of ground water near lakes in a multi-lake system that contains aquifers. Aquifers are shown as rectangular, stippled areas. K_h/K_v = vertical hydrologic conductivity; K_{ag}/K_t = ratio of the hydraulic conductivity of aquifers to that of the surrounding till. (From Winter 1976)

important and very complicated temporally and spatially. Some sediment areas provide in-seepage and others have out-seepage; seepage flow rates generally increase toward the shoreline (Asbury 1990). Preliminary estimates suggest that seepage outputs from the lake could account for more than 40% of the total annual water loss from the lake (Likens et al. 1985b).

Concluding Remarks. *It is important to be interested in species, ecosystems, chemistry and habitats, but linkages and interactions predominate in ecological relationships. Narrowly focused interest on one of these topics may detract from a focus on the linkages and interactions. A narrow focus, therefore, can act as a “blinder” to fuller understanding. Although it may be easier, it is inefficient in ecological studies to keep blinders on our individual approaches. Ecologists must try to integrate diverse information, to take the blinders off and look both within and “beyond the shoreline” (Likens 1984) if we’re going to find comprehensive answers and develop a fuller ecological understanding.*

The need to understand the ecological linkages at the level of ecosystems is crucial for management. The ecosystem concept provides an important framework for studying these interactions. The transport of materials through the atmosphere to ecosystems remote from the emission sources is one important linkage between ecosystems of the biosphere. These interactions must be quantified, evaluated and understood if such pollutants are to be managed and mitigated in today’s world.

A quantitative and integrated knowledge of the linkage between hydrology and biogeochemistry is critical for the management of the vital air-land-water linkage. For example, there are hydrological and biogeochemical linkages of great importance to consider relative to the potential effects of global climate change. These linkages are enormously complex, and trying to understand them is one of the biggest scientific challenges today. Nevertheless, these linkages provide not only the poetry of ecosystems, landscapes and regions, described by Aldo Leopold, but the basis for their understanding.

III

ECOSYSTEM ECOLOGY AND SOCIETY

(1) The Water Crisis

“When the well is dry
is when we know the worth of water.”

Benjamin Franklin
[*Poor Richard's Almanac*
(1746), January]

General Aspects

By all accounts, it is clear that one of the most serious environmental problems of the 1990's will be the availability of useable water for human consumption, domestic use, agriculture and aquaculture. By useable, I refer to water that is not toxic to biological organisms. Thus, useable water cannot be seriously contaminated by organic and inorganic pollutants, including salt, and heat. Although global projections are difficult to make, it seems certain that because of expected increases in the size of the human population, water use and pollution will continue to increase globally for at least the next several decades. Because of these projections and the vital nature of water, many have predicted that water will become the critical resource problem in the world during the 1990's (e.g. Biswas 1991).

The planet Earth is richly endowed with water. As such it is unique within the planetary system as we know it. Some 99% of the water on the Earth is unavailable, however, for direct human use. It is either too salty or is frozen (see Water Resources Institute 1988). Massive amounts of energy are required to convert salty or frozen water into available fresh water.

A few freshwater lakes, such as Lake Baikal in Siberia and the five Laurentian Great Lakes of North America, contain vast quantities of fresh water. Lake Baikal contains about 12% and the Laurentian Great Lakes contain an additional 13% of all the surface fresh waters (including soil water, but not ground water) on our planet (Wetzel 1983). Thus, in these six lakes is found about 25% of all the surface fresh waters for the Earth. As such, these six lakes represent a resource treasure vital to life.

The Global Water Problem

Assuming that about 64% of the annual precipitation falling on all land surfaces is returned to the atmosphere by evaporation and transpiration, some 37000 km³ of water yr⁻¹ potentially could be available to humans on the planet (Water Resources Institute 1988, p. 187). If divided evenly among the current world population of about 5.4×10^9 (Anonymous 1991b), some 19000 liters day⁻¹ could be available to each person. Obviously, water is not distributed evenly or equally among the peoples of the world. Indeed, desertification is widespread and increasing in arid and semi-arid areas like Ethiopia, as a result of deficit water balances, frequently accentuated by overpopulation and overgrazing of the natural ecosystem (Ehrlich and Ehrlich 1990, World Resources Institute 1990). Conflicts about the availability of scarce fresh water in arid regions like the Middle East frequently generate volatile political problems as well.

The human population now may exceed 5.4×10^9 people and is increasing at a rate of about 93 million per year (Anonymous 1991b). Most of this projected population increase is expected to occur in developing countries like those in Asia and central and west Africa. As these countries grow and “develop” they undoubtedly will have a demand on resources, especially water, greater than that expected simply on the basis of population increase. Thus, developed, and particularly developing, countries throughout the world face serious questions of resource management as human populations increase, and as regional- and global-scale pollution increases in relation to these population increases. But what if rates of pollution were to increase faster than rates of human population increase, as it has in developed countries? The Earth’s population has doubled during the past 40 years and probably will double again in the next 50 years or so, to about 10 billion. Where will almost ten billion people find suitable water resources to maintain a reasonable standard of living, let alone to survive?

Because of dismal conditions relating to availability of suitable water in developing countries, an International Drinking Water Supply and Sanitation Decade was launched in November 1980 (see Christmas and de Rooy 1991). On average, impressive improvements in the supply of water for drinking and in sanitation services occurred in developing countries, particularly in rural areas, during the decade (Fig. 45). Overall, however, there are still about 31% of the population without water and 43% without

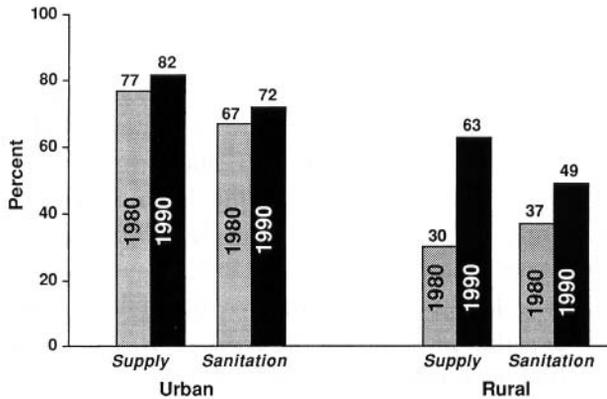


Fig. 45. Water supply and sanitation service provided for urban and rural sectors of developing countries in 1980 and 1990. (From Christmas and de Rooy 1991; modified)

sanitation services in these developing countries (Christmas and de Rooy 1991). In the world's least developed countries progress was very slow. In such countries in Africa, for example, only 33% of the rural population had a reliable supply of drinking water in 1980. This proportion had increased to only 42% by 1990 (Christmas and de Rooy 1991). Based on projected population increases, it is anticipated that more than 2×10^9 additional people in these developing countries will require these vital services by the year 2000 (Grover and Howarth 1991). It has been proposed that by the year 2025, some two-thirds of the African population will be severely water stressed (Falkenmark 1989).

Lowering of water tables in major aquifers is now common throughout the world because of heavy demand on this water by humans for irrigation, industrial activities and domestic use. In spite of the value of this resource, waste is prevalent in each of these uses, and at all levels. For example, the flooding of agricultural fields for irrigation is still common in many areas rather than the more expensive, but far more efficient use of spray, and particularly drip, irrigation procedures.

For the world, there has been about a five-fold increase in irrigated land since 1900 (Postel 1989). In arid and semi-arid regions irrigation and so-called dry-land farming can lead to increased salt concentrations in soils and surface waters, by the process known as salinization (Williams 1987, Postel 1989). Salinization can render water unfit for drinking, and further irrigation use.

The United States Water Problem

Our lavish, wasteful use of water in the United States has given modern meaning to Franklin's statement. The issue is not only whether there is enough water but also whether the water is suitable for human use.

About 25% of the water that falls on the United States each year as precipitation infiltrates the soil and recharges local aquifers. In 1985 about 22% of the freshwater withdrawals in the United States were from ground water (Moody 1990). These withdrawals provided drinking water for about 53% of the US population. Only eight states (Arizona, Arkansas, California, Florida, Idaho, Kansas, Nebraska, Texas) use 66% of the total ground water withdrawn each year in the US, and most of this water was used for irrigation (Moody 1990).

Every day the public water systems of the United States provide, on average, every person with about 160 gallons (605 liters) of water. Considering the total population (250 000 000) in the United States, this requires about 40 billion gallons (1.5×10^{11} liters) of water a day. Based on the expected population increase for the United States, in 50 years some 50 billion gallons (1.9×10^{11} liters) of water per day will be required if the per capita use were to stay the same. On average it requires about 100 000 gallons (378 500 liters) of water to produce one automobile, 60 000 gallons (227 100 liters) to produce one ton of steel, 1500 gallons (5678 liters) to produce one cotton dress, and 10 gallons (38 liters) to produce one copy of a book like this one (Powledge 1984). A typical family of four in the United States uses about 10 gallons (38 liters) per day for drinking and cooking, about 15 gallons (57 liters) per day to wash dishes, 98 gallons (371 liters) per day for toilets, 80 gallons (303 liters) per day for bathing, 35 gallons (132 liters) per day for laundry and about 100 gallons (379 liters) per day for watering the lawn, washing the car and so forth. Thus, about 338 gallons (1279 liters) per day are used by a typical family of four, of which only 3% is used for cooking and drinking. Typically, a toilet in the US requires about 4 gallons (15 liters) for each flush. The so-called water-saver models require about 2.5 gallons (9.5 liters). Such unnecessary "waste" of water in the US is far greater than in most other countries of the world.

The per capita use of water in New York City has increased from about 25 gallons (95 liters) per day in the nineteenth century to about 150 (568 liters) in 1970 and to about 207 (780 liters) in 1990. Thus, the population of New York City "requires" on the average about 1.5 billion gallons (5.7×10^9 liters) of water per day (Anonymous 1991d). The average single family

household in New York City uses about 73 000 gallons (276 300 liters) per year (circa 1989) at a cost of about \$184 per year (Parker 1989).

Pollution and Management Concerns

Recent public opinion polls in Argentina, Brazil, People's Republic of China, the Federal Republic of Germany, Hungary, India, Japan, Norway, Saudi Arabia, Senegal and Zimbabwe listed pollution of water as one of the two most worrisome environmental problems. In the People's Republic of China, Argentina, India, Japan and Hungary, it was the major concern (Anonymous 1991e). Some 84% of the US public believe that water pollution is a serious environmental problem (Little 1989).

Water quality problems in the US have become more common during recent decades. In the early 1970's news media accounts frequently reported that Lake Erie was "dead." In fact, Lake Erie was never dead. The problem with Lake Erie was that it was too much alive. It had been enriched with nutrients to the point where it became highly productive, a process known as eutrophication. The abundance of nutrients, primarily nitrogen and phosphorus input from human activities, produced extensive algal blooms. Some of these algae caused a nuisance for water supplies because of unpleasant odors and tastes. When excess algae died and settled to deeper waters of the lake, dissolved oxygen was depleted, thereby adversely affecting fish and invertebrate populations. Nevertheless, the publicity by the news media that Lake Erie was dying or dead helped to pass in 1972, strict Amendments to the Clean Water Act (see p.105 ff.). In fact, this legislation was adopted unanimously in the US Senate!

The problems of cultural eutrophication of aquatic ecosystems have been apparent for a long time (e.g. Hasler 1947, Likens 1972, Hutchinson 1973). Such problems may have lessened in lakes like Erie (see p. 57 ff.), but have not disappeared because of legislative action, such as passage of a Clean Water Act. Cultural eutrophication continues as a varied and complex environmental problem. When fresh waters are enriched with nutrients, plant growth can become excessive, to levels that humans find undesirable unless they want to grow fish, like carp, as an aquacultural source of protein. In that latter case, eutrophication is not viewed as bad; it is desirable. What do we want or need? And who is "we"? How does "we" relate to desires and needs of people in developed versus developing countries?

The pollution of drinking water supplies throughout the world also is not a new problem, as human populations diligently have followed the engineering adage “Dilution is the solution to pollution,” and have used lakes and streams as convenient receptacles in attempts to keep wastes “out of sight and out of mind.” However, increasing industrial activity, urban density, and increasing numbers of humans worldwide have made it impossible to keep these pollutants out of sight and mind. Indeed, increased public concerns about the safety of drinking water have emerged recently in the United States (e.g. Goldfarb 1989, Abelson 1990). For example, it is believed that lead in drinking water may contribute up to 20% of a person’s total exposure to this toxic metal, and thereby be one of the factors contributing to increased concentrations of lead in the blood of humans (Table 11).

“In Köhln, a town of monks and bones,
And pavements fang’d with murderous stones
And rags, and hags, and hideous wenches;
I counted two and seventy stenches,
All well defined, and several stinks!
Ye Nymphs that reign o’er sewers and sinks,
The river Rhine, it is well known,
Doth wash your city of Cologne;
But tell me, Nymphs, what power divine
Shall henceforth wash the river Rhine?”

Samuel Taylor Coleridge
1772–1834
Cologne

Contamination of groundwater supplies is one of the world’s most serious environmental problems (e.g. Moody 1990, Anonymous 1991c, Hughes 1991). In deep aquifers it may take tens of thousands of years for ground water to reach discharge points. Thus, normally there is a very long delay in detecting contaminants and, likewise, for flushing them from the aquifer. Contamination of groundwater supplies in developed countries is a particularly vexing and expensive environmental problem. Contamination may result from a variety of human activities (Table 12).

In 1979 it was discovered that the major San Gabriel Aquifer near Los Angeles, California (USA), had been contaminated with toxic volatile organic compounds (VOCs) such as trichloroethylene, perchloroethylene and carbon tetrachloride. It is estimated that it will require 30 to 50 years to

Table 11. Percentage of the children (6 months to 5 years) in large (>1 million) US cities that have unacceptable levels* of lead in their blood. Modified from *USA Today* [8 May 1991]

City	% of children with unacceptable blood levels of lead
New York City	75
Newark	71
Boston	69
Cleveland	65
Buffalo	62
Philadelphia	62
Chicago	61

* Recent evidence suggests that blood levels as low as 10 to 15 $\mu\text{g Pb liter}^{-1}$ may have adverse neurobehavioral effects in children (Brett and Plunkett 1991)

clean up this contamination at a cost of some \$800 million (Anonymous 1991c). Five states each have more than 77 toxic waste dumps on the US Superfund National Priorities List (New Jersey, 109; Pennsylvania, 95; California, 88; New York, 83; and Michigan, 77). The thoughtless release of these poisons has produced one of the United States' most serious and expensive environmental problems, which threatens both surface and groundwater supplies.

Here I will address briefly only one type of contamination of surface and groundwater supplies. I will focus on nitrate pollution, because this developing environmental problem provides an excellent example of the complexity, severity, diversity of sources (e.g. Table 12), and widespread nature of the contamination. The scale and complexity of this environmental problem underscore the need for the ecosystem approach in developing comprehensive management solutions.

Nitrate contamination of aquatic resources

Peierls et al. (1991) have shown recently an important relationship between density of humans and both concentration and export of nitrate in major rivers of the world (Fig. 46). Excessive nitrate levels in surface water, ground waters and coastal waters can lead to algal blooms and toxicity problems for human consumption. Increased nitrogen content in surface and ground waters may have numerous sources: animal (including human)

Table 12. Activities contributing to groundwater contamination. One acre equals 0.405 ha. (From Moody 1990; modified)

Activity	States citing	Estimated sites	Contaminants frequently cited as result of activity
Waste disposal			
Septic systems	41	22 million	Bacteria, viruses, nitrate, phosphate, chloride, organic compounds such as trichloroethylene
Landfills, active	51	16 400	Dissolved solids, iron, manganese, toxic metals, acids, organic compounds, pesticides
Surface impoundments	32	191 800	Brines, acidic mine wastes, feedlot wastes, toxic metals, organic compounds
Injection wells	10	280 800	Dissolved solids, bacteria, sodium, chloride, nitrate, phosphate, organic compounds, pesticides, acids
Land application of wastes	12	19 000 land application units	Bacteria, nitrate, phosphate, toxic metals, organic compounds
Storage and handling of materials			
Underground storage tanks	39	2.4–4.8 million	Benzene, toluene, xylene, petroleum products
Above-ground storage tanks	16	Unknown	Organic compounds, acids, metals, petroleum products
Material handling and transfers	29	10 000–16 000 spills yr ⁻¹	Petroleum products, aluminum, iron, sulfate, toxic metals
Nuclear weapons complex	12	> 15	Radioactive materials, organic compounds such as trichloroethylene, toxic metals, acids, nitrate
Mining activities			
Mining and spoil disposal, coal	23	15 000 active/ 67 000 inactive	Acids, iron, manganese, sulfate, uranium, thorium, radium, molybdenum, selenium, toxic metals
Oil and gas activities			
Wells	20	550 000 production; 1.2 million abandoned	Brines

Table 12 (continued)

Activity	States citing	Estimated sites	Contaminants frequently cited as result of activity
Agricultural activities			
Fertilizer and pesticide applications	44	363 million acres	Nitrate, phosphate, pesticides
Irrigation practices	22	376 000 wells; 49 million acres irrigated	Dissolved solids, nitrate, phosphate, pesticides
Animal feedlots	17	1900	Nitrate, phosphate, pesticides
Urban activities			
Runoff	15	47.3 million acres urban land	Bacteria, hydrocarbons, dissolved solids, lead, cadmium, toxic metals
De-icing chemicals			
Storage and use	14	Not reported	Sodium chloride, ferric ferrocyanide, sodium ferrocyanide, phosphate, chromate
Other			
Saline intrusion or upcoming	29	Not reported	Dissolved solids, brines

waste discharges (e.g. Moody 1990); atmospheric deposition (e.g. Fisher and Oppenheimer 1991; p. 50 ff.); application of nitrogenous fertilizers to forested lands (e.g. Hetherington 1985, Edwards et al. 1991, Tamm 1991) or to agricultural lands (e.g. Moody 1990); deforestation (e.g. Likens et al. 1970); and industrial effluents (e.g. Moody 1990; see also Table 12). Thus, various human activities – in various combinations – can cause the enrichment of inorganic nitrogen in aquatic ecosystems, but it would appear that increasing size of the human population is the root cause.

Nitrate-nitrogen concentrations higher than 3 ppm often suggest the presence of human activities. Primary drinking water standards in the United States require that concentrations of $\text{NO}_3\text{-N}$ be less than 10 ppm (US Environmental Protection Agency 1976). High concentrations of nitrate may be reduced by bacteria to nitrite in the intestines of infants causing methemoglobinemia (blue baby syndrome). Infant mortality from this

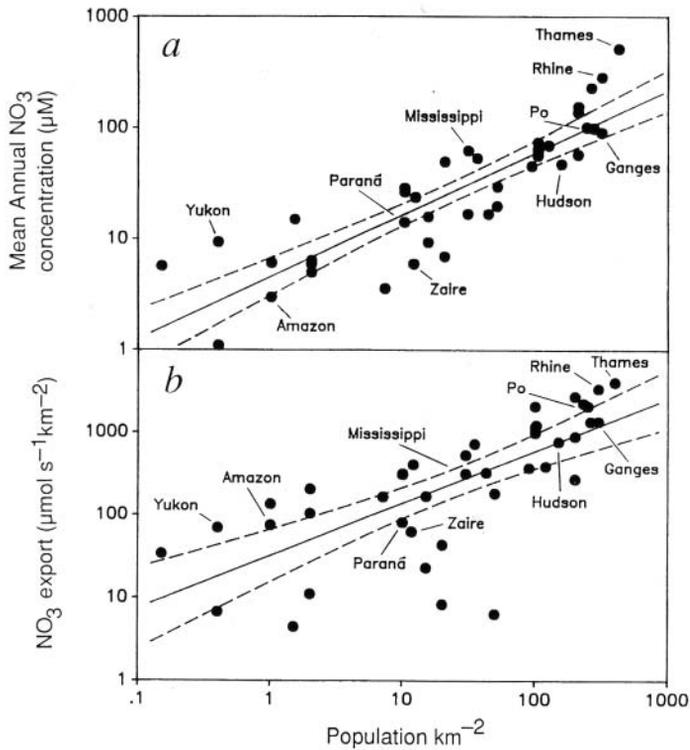


Fig. 46. Relationship between average annual nitrate concentration (a) and export (b) in 42 rivers of the world and human population density. Dashed lines are 95% confidence intervals for the regression; r^2 for (a) = 0.76, for (b) = 0.53. (From Peierls et al. 1991; modified)

disease increases when nitrate-nitrogen concentrations are above 10 ppm. Nitrate also can react with amines in humans to form carcinogenic nitrosamines. Levels of $\text{NO}_3\text{-N}$ exceeding 10 ppm have been found in 6% of the wells sampled in the US (Moody 1990).

Animal wastes. Human septic systems represent the largest source of waste, by volume, discharged to the land each year. It is estimated that between 820 and 1460 million gallons (3100 to 5500 million liters) of waste from septic systems are released to shallow aquifers in the US each year (Moody 1990). These wastes are a major source of nitrate, as well as bacteria, viruses, phosphates, sodium chloride and organics for water supplies. Some 500 000 new domestic disposal systems are installed each year in the US (Moody 1990). In comparison to the septic wastes, municipal and industrial activities generate about 150×10^6 and 240×10^6 tons (136×10^6 and

218×10^6 metric tons) of solid waste, respectively, each year in the US (Moody 1990). Sewage loading can occur directly to surface water supplies such as rivers or lakes, or can infiltrate the soil and contaminate ground-water supplies.

Atmospheric deposition. Significant amounts of nitrogen can be added to aquatic and terrestrial ecosystems through wet and dry atmospheric deposition (see p. 50 ff.), and thus contribute to elevated nitrate concentrations in surface and ground waters. During the 1960's inorganic nitrogen concentrations generally increased in eastern North America and northwestern Europe (e.g. Fig. 10; van Breemen and van Dijk 1988), presumably due to increased anthropogenic emissions of nitrogenous gases (e.g. Fig. 16; Butler and Likens 1991). Estimates for dry deposition of nitrogen are highly uncertain and variable, but may be equivalent to wet deposition inputs of nitrogen in eastern North America (Levy and Moxim 1987) and northwestern Europe (Derwent and Nodop 1986). Moreover, atmospheric inputs of nitrogen from cloud water to ecosystems at high elevations may be up to five-fold greater than that from wet deposition (Lovett et al. 1982, Lovett and Kinsman 1990, Vong et al. 1991). Fisher and Oppenheimer (1991) have estimated that atmospheric inputs of nitrogen can contribute some 37% of total, annual nitrogen inputs to the Chesapeake Bay Estuary, USA. Some 64% of these atmospheric inputs were added as nitrate-nitrogen. In comparison, animal waste and fertilizer were estimated to contribute 31 and 25%, respectively, of the total nitrogen inputs to the estuary. Nearly 100% of the total, annual nitrogen inputs to the Hubbard Brook Experimental Forest are derived from wet and dry deposition from the atmosphere (Bormann et al. 1977, Likens et al. 1977). Nitrate comprised about 70% of the inputs in wet deposition (see p. 50 ff.). Inputs of nitrogen in excess of assimilation and storage within a terrestrial ecosystem can result in nitrogen saturation (e.g. Ågren and Bosatta 1988, Aber et al. 1989, 1991; p. 53) and loss of the excess nitrogen as nitrate in drainage water.

Fertilizers. Increased amounts of nitrogen, phosphorus and potassium fertilizers have been used widely throughout the world during recent decades to maximize crop production (e.g. Tamm 1991). In the United States, fertilizer use increased steadily from about 1960, peaking in 1981 at about 21 million metric tons yr^{-1} (Fig. 47). A large proportion of this increase was due to the use of nitrogenous fertilizers on corn and wheat (Moody 1990). Typically, nitrogenous fertilizers are added to the soil as a mixture of ammonium, nitrate and urea. Urea may be mineralized to ammonium, and ammonium nitrified to nitrate by bacteria. When applications of

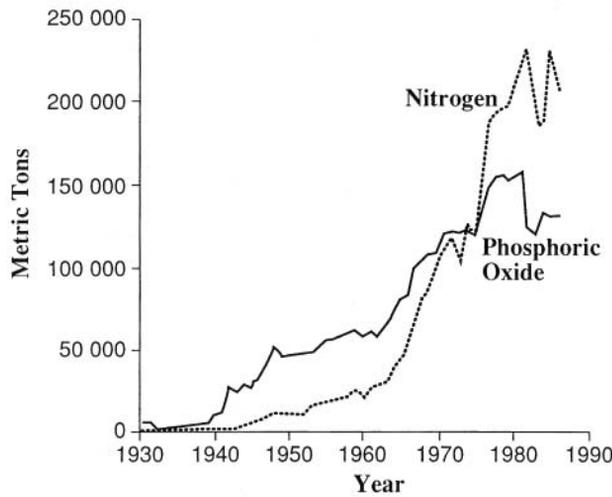


Fig. 47. Trends in fertilizer use since 1930 in Wisconsin, a major agricultural state in the USA. (From Mason et al. 1990; modified)

nitrogenous fertilizers exceed the amount taken up by plants, the excess can leach in runoff and to ground waters, primarily as the more mobile anion, nitrate (e.g. Kohl et al. 1971, Gold et al. 1990, Mason et al. 1990, Moody 1990). Nitrate concentrations in many major aquifers in agricultural states

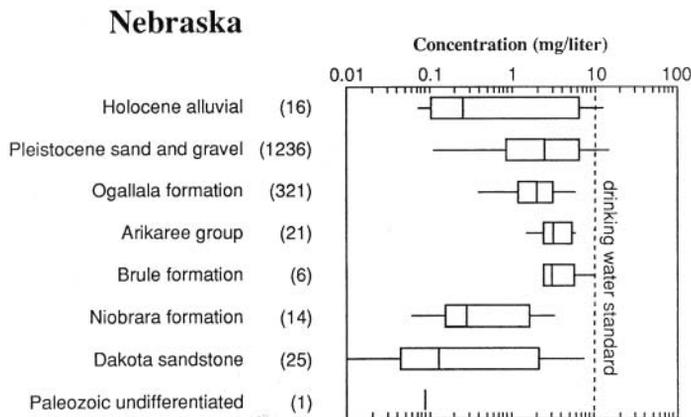


Fig. 48. Concentration of nitrate-nitrogen in principal aquifers in the state of Nebraska (USA), compared to the national primary drinking water standard. (From Mason et al. 1990; modified)

of the US now commonly approach or exceed primary drinking water standards (Fig. 48). In addition to problems of water pollution, it has been estimated that farmers in Wisconsin, for example, lose about \$27 million yr^{-1} (as much as \$3.50/ha-yr) from applying more fertilizer than is needed to optimize crop production (Lisher 1991).

Deforestation. One of the discoveries at Hubbard Brook was that when the forest is disturbed, e.g. by harvesting, the nitrogen cycle is altered significantly. Whereas nitrogen is held tightly by an aggrading forest, following disturbance, decomposition of organic matter is increased, microbial nitrification is accelerated and large amounts of nitrate are lost in drainage waters (Likens et al. 1970). The concentrations of nitrates in stream water draining deforested watersheds can exceed those that are acceptable for drinking water (Likens et al. 1970, p. 105 ff.). This pattern has been found in several other locations and forest types (e.g. Vitousek et al. 1979). The amount of nitrate loss depends on many factors, however, including type of forest, soil characteristics, and timing and extent of disturbance.

The critical role of microorganisms in regulating the nitrate concentrations in surface and ground water is obvious from these examples. The mineralization of organic matter to release ammonium, the oxidation of ammonium to nitrite and nitrate (nitrification), and the reduction of nitrate to nitrite or to gaseous forms of nitrogen (denitrification) all are done by bacteria. Understanding the role of these microorganisms in diverse ecosystems is central, not only for understanding the nitrogen cycle, but for management of this emerging environmental problem.

Industrial wastes. Certain industrial wastes also may contribute to nitrate pollution of surface and ground waters (Table 12). These point sources are variable in importance, but as point sources they potentially are easier to regulate and manage.

Concluding Remarks. *The problems of limited availability of suitable water for human use are currently severe and widespread throughout the world. These problems require prompt attention and action. This emerging crisis in water availability will have to be met in the short term by conservation, desalination (e.g. Abelson 1991) and melting of ice. Obviously, desalination and melting of ice require huge inputs of energy. In 1990 the US Congress authorized 1992 as the "Year of Clean Water" (October 1992 is to be Clean Water Month). This is a nice idea, but worthless without the backing of politicians and of all individuals, who must be dedicated to making a*

difference by practicing conservation and supporting fair pricing of the environmental value of this vital resource. These practices should include: water-efficient irrigation, maintenance of public water supplies to prevent leakage, water-efficient landscaping (use of grey-water as is currently done in some areas in California and elsewhere), reduced lawn size and maintenance, and water-efficient toilets and showers.

The potential of global climate change adds new, long-term dimensions to this environmental problem. Global climate change could easily change the 'haves' into the 'have nots' relative to water supply, as well as further accentuate the overall problem. As a result of global climate change, sea levels could rise or there could be an increase in frequency and intensity of storms causing flooding of low-lying urban centers, e.g. London, Sydney, Bangkok, Dhaka (Jacobson 1989, Anonymous 1991a). Such changes would add greater urgency to an already emerging crisis situation pertaining to water resources.

(2) Environmental Issues, Scientific Communication and Ethics

“All I know is what I read in the papers.”

Will Rogers
ca. 1930

Solving environmental issues, in contrast to questions in ecological science, must include the added complexity of political and economic factors, as well as social values. Environmental issues tend to become single-focus fads, rising to great visibility and then almost as quickly disappearing from public attention. Although the temporal dimensions of ecological questions commonly are long term (i.e. more than one year), funding for scientific research typically has been based on annual allocations. Funding for a scientific research project may be continued, in part, because the prior efforts or their results were visible. Such scientific visibility can occur when results are published in high-quality, peer-reviewed journals. Second, visibility may be attained when diverse results are brought together and integrated (referred to as “synthesis” in today’s scientific jargon), primarily in books. A third way that results become visible is when they generate controversy. Based on my experience with the Hubbard Brook Ecosystem Study, I will address some of these points about visibility, particularly as they pertain to sustaining research efforts during long periods and to resolving environmental questions.

An early experiment at Hubbard Brook tested an ostensibly simple question, “What happens to a forested ecosystem when all of the trees are removed?” We cut all of the trees on an entire watershed-ecosystem during 1965, and prevented regrowth for three years (Fig. 49). We wanted to experimentally remove all living vegetation from the ecosystem to test the biogeochemical response. As a result of this deforestation, the chemistry of the stream water changed dramatically, especially the concentrations of nitrate. Six months after the trees were killed the concentrations of nitrate in stream water increased markedly and in the second year increased to even higher levels (Fig. 50), exceeding the concentrations allowed for drinking water in public water supplies (Likens et al. 1970).



Fig. 49. Experimentally deforested watershed at the Hubbard Brook Experimental Forest, New Hampshire, USA. This watershed-ecosystem was deforested in 1965 and maintained in that condition with herbicides for three years, before vegetation was allowed to grow. Cut trees were left in place instead of being removed as would be the case in a normal timber harvest. (Photo by G. E. Likens)

A major drought was occurring during the period 1964 to 1966 in the northeastern United States. During this time it was necessary to *ask* for a glass of water in a restaurant in New York City – an uncommon situation in the United States. And there were semi-serious proposals “...to cut those trees in New England that were wasting water by evapotranspiration, to produce more liquid water for the thirsty megalopolis between Boston and New York City.” The Hubbard Brook results, however, suggested that such water might not be suitable for drinking. Unprecedented algal blooms (*Ulothrix zonata*) in the stream of the experimentally deforested watershed-ecosystem also attested to the increased concentrations of nutrients in the drainage waters. These nutrients were coming primarily from decomposition of organic matter in the forest floor (Likens et al. 1970), and, thus, to some observers it appeared that the upper soil horizons were being impoverished of nutrients.

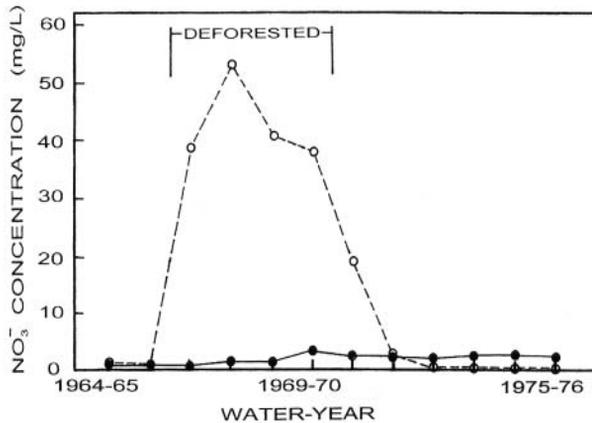


Fig. 50. Annual, volume-weighted nitrate concentrations in stream water from deforested Watershed 2 (o) and reference Watershed 6 (●) of the Hubbard Brook Experimental Forest from 1964–65 through 1975–76

Also at this time, the United States Senate was actively considering the regulation of clearcutting of forests, primarily in the western United States. Those opposed to clearcutting used data from Hubbard Brook to suggest that the soils in the western US would become “sterile” following clearcutting. Interestingly, we had published our data actively and aggressively in scientific journals (e.g. Bormann et al. 1968, Likens et al. 1969, 1970, Hornbeck et al. 1970, Pierce et al. 1970), but only once were we asked to comment in Congress relative to the emotional clearcutting issue.

At one point in this process, a Program Officer of the National Science Foundation (NSF), in reviewing our proposal for continuing research at Hubbard Brook, told us that the NSF would continue to fund our research, essentially providing all the money that we had asked for, but that we would not be allowed to continue study of forest cutting because the results were embarrassing to another federal agency. The “embarrassment” resulted apparently from the fact that clearcutting was an accepted federal policy for harvesting timber and our results indicated that there were potential environmental problems. We fought this “decision” through the bureaucracy to the Director of the NSF, and we succeeded in convincing the NSF that we should be allowed to study the effects of clearcutting if our proposals were judged worthy scientifically by peer review. In fact, we have continued such studies until the present time.

A second controversy emerged when we learned from our earliest samples that the rain and snow at Hubbard Brook were quite acid, averag-

ing about pH 4.1 in 1964. We thought this result was very interesting, but did not know how widespread it might be because there were too few measurements in North America to compare. It was not until I set up some monitoring stations in the Finger Lakes Region of New York State in 1969 that I discovered that the rain and snow there essentially had the same pH as we were measuring at Hubbard Brook in the White Mountains of New Hampshire (Fig. 51; Likens 1989b).

My colleagues and I published the first paper about acid rain in North America in 1972 (Likens et al. 1972 [I use “acid rain” here in the popular sense, referring to all components of wet and dry deposition of acidic substances]). A Swedish scientist, Svante Odèn, already was writing about the acidity of rain in Scandinavia (Odèn 1968). We used the term “acid rain” in the title of our first paper (Likens et al. 1972) without knowing that the term had been used more than 100 years before by a scientist in England (Smith 1872). Frankly, we chose this phrasing for its potential visibility and impact. Our second paper on acid rain was published in *Science* (Likens and Bormann 1974), and a week after it was published, the results were described on the front page of *The New York Times*, 13 June 1974 – with tremendous visibility!

Some 70% of total sulfur emissions in the US occur from the combustion of fossil fuels in the production of electricity, largely in the Tennessee and

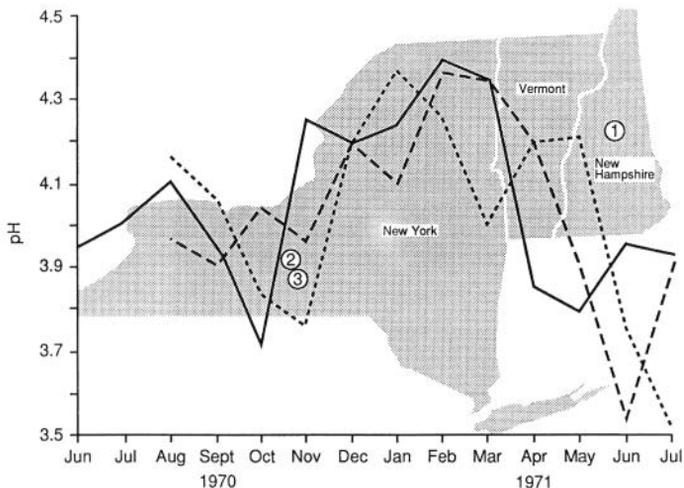


Fig. 51. Volume-weighted pH of rain and snow at the Hubbard Brook Experimental Forest, New Hampshire (1; —), Aurora, New York (2; ----) and at Ithaca, NY (3; -.-) from 1970 to 1971. (From Likens 1989b; modified)

Ohio River Valleys, and as the air moves from west to east the sulfur is transported to the northeastern US (Likens et al. 1979, p. 63 ff.). This aspect of the phenomenon, where somebody is generating waste, “garbage” if you will, and dumping it on somebody else can be a highly “visible” and controversial feature of the problem, and can have a large emotional impact.

Today probably more than 10 000 scientific articles, a dozen or so major federal reports, and a vast number of popular reports have been written about the topic of acid rain. It is now well accepted that winds can transport toxic materials of many kinds throughout the global atmosphere (e.g. Brown 1987).

Highly visible cartoons about acid rain have been common in the news media during the past two decades, and in my opinion, have influenced public opinion significantly. In the 1970’s these cartoons frequently showed skeletons of fish from acidified lakes, suggesting that the flesh of fish had dissolved away in the acid waters and left only the skeleton. Obviously, just the reverse might make more sense in extreme conditions, but neither is correct, and that brings me to one of my main points.

The Premise

Environmental issues usually are adopted by the vested interests of many different groups, e.g. “environmentalists” on one side and “industrialists” on the other. Should scientists ride on their white steeds, dressed in shiny armor between these two forces, fending off exaggerations from both sides, or should they only pursue truth from the dusty corners of their laboratories? Obviously these options are at the extremes for scientific activity. An example of the non-scientific exaggerations and half-truths is seen in an article, published in 1986 in *Fortune Magazine* by W. M. Brown. The article stated “. . . that acid rain is only a minor contributor to the environmental damage. . . . So far as the lakes are concerned, the principal sources of damage are likely to be natural sources of acid. . . . The amount of acid generated by nature is now known to be far greater than that contributed by industrially-generated acid rain. Take bird droppings, which are a relatively minor contributor to the problem. A calculation based on Audubon Society data shows that the droppings hit the US at a rate of about one million per second, and the 150 million tons of droppings per year outweigh sulfur dioxide emissions by something like six to one.” It didn’t seem to concern Mr. Brown that sulfuric acid, not uric acid (in bird feces), is the dominant

acid in recently acidified lakes, such as those in the Adirondack Mt. region, that bird droppings are not focused on these lakes, that bird populations have not increased dramatically in the last fifty years, but SO₂ emissions have, and so forth. How does this naive (or contrived) confusion between apples (bird droppings) and oranges (anthropogenic SO₂ emissions) help to resolve an important environmental question? It doesn't! Similar disinformation, generated by industries with vested financial interests, apparently now is being produced relative to the issue of global warming (Amato 1991).

Two colleagues and I wrote an article, published in a peer-reviewed scientific journal, called "Red Herrings in Acid Rain Research" (Havas et al. 1984). A red herring was defined as, "... a diverting of attention from the main subject by introducing some irrelevant topic." We wondered why anybody intentionally would want to generate red herrings relative to scientific issues. We suggested that a number of red herrings about the acid rain issue had been generated by industrial groups, and explained why they were red herrings. We wrote the paper out of frustration at the exaggerations and half-truths being generated, largely in the non-scientific literature. Is it appropriate for a scientist to write such papers?

A Pattern

The general pattern of public response to such environmental issues is remarkably similar – whether the issue is the role of phosphates in eutrophication, or pesticides and their ecological effects, or disposal of toxic wastes, or destruction of stratospheric ozone, or the ecological effects of nuclear war including nuclear winter, or acid rain. The pattern seems to be that first someone identifies a potential "problem" (Fig. 52). The problem simmers along until for some reason it becomes highly visible, usually by getting into the popular press. Relative to the pesticides issue, visibility came with one book, *Silent Spring*, by Rachel Carson (1962), a powerful bestseller. At that point "awareness" goes up dramatically, and people start pointing fingers. Who caused this problem? Somebody did it! Who is going to pay for it? And then the "reaction" – "No, not us," "We didn't do it," "You must be wrong," or "The data must be faulty."

In the phosphorus/eutrophication debate during the late 1960's–early 1970's, Canadian Research and Development (CR&D) produced a slick issue (March/April 1970) of their magazine during this reaction phase. This

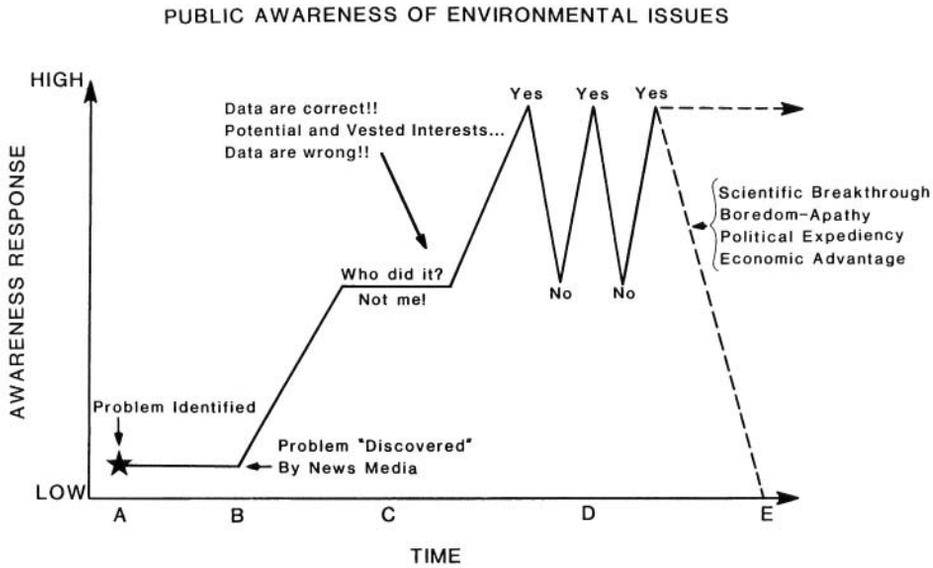


Fig. 52. Pattern of awareness and response to environmental issues

CR&D issue looked somewhat like *Time Magazine* in format and in size. The front cover was mostly black with a red border and in the center was a noose (Fig. 53). In the middle of this cover page it said, “We hung phosphates without a fair trial.” A major portion of the issue attempted to discredit Dr. Jack Vallentyne, a prominent limnologist from Canada, who had argued that the removal of phosphates from detergents would help to alleviate eutrophication of freshwater lakes, particularly in the Laurentian Great Lakes. Quoting from CR&D, “Certainly, however, the ludicrous banning of phosphates in detergents will bring us not one whit closer to any eutrophication solution. Rather than clean the waters, it will only serve to muddy them still further” (Legge and Dingeldein 1970, p. 27). In describing activities during 1969 of the International Joint Commission (IJC) on pollution in the Laurentian Great Lakes, Legge and Dingeldein questioned whether the IJC had “...been a party to what may prove to have been the most incredible scientific/political hoax in the history of Canadian and American relations” (p. 19).

The point that they were trying to make was “...an amazing story. Revealed for the first time is a new account of a principal process of eutrophication that shows carbon, not phosphorus, to be the controlling nutrient in the production of algal bloom” (p. 19). The CR&D editors opined that “The

**CANADIAN RESEARCH
& DEVELOPMENT**
A MACLEAN HUNTER PUBLICATION MARCH/APRIL 1970

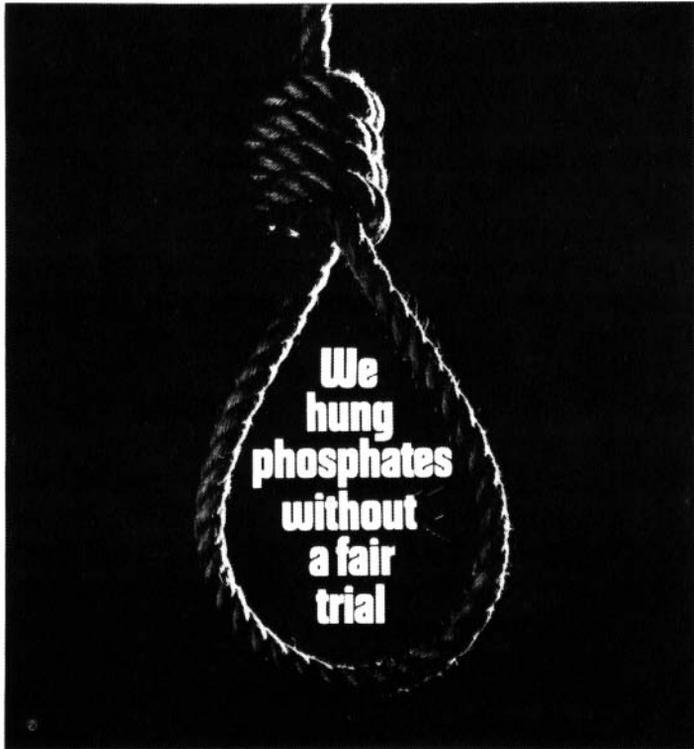


Fig. 53. Front page from March/April 1970 issue of Canadian Research and Development

trouble is, it is a safe bet that the conclusions reached in his [Valentyne's] 'naive' experiments have been accepted by Canada's legislators as proof of the key role of phosphates in eutrophication, yet for this purpose they require concrete scientific validation and this has not been produced" (Anonymous 1970, p. 40). Thus, the conclusion was that study, not action, was required.

Vallentyne defended himself in a reasoned and eloquent article in the next issue of CR&D (Vallentyne 1970). Regarding the issue of public understanding and action he stated, "When confusion and controversies arise on the subject of eutrophication they can usually be traced to statements and opinions given by novices in limnology or by experts in other areas, when they extrapolate their experience beyond its legitimate boundaries. When this happens, it is unfortunate for all parties concerned, particularly for the general public who become discouraged with what they can only regard as confusion and disorder" (p. 36).

Increased attention was given to the eutrophication issue by scientists in the United States and Canada, either in association with the developing controversy or directly as a result of it. There was an increase in scientific research and particularly scientific meetings and reports (e.g. Anonymous 1969, International Lake Erie and Lake Ontario - St. Lawrence River Water Pollution Boards 1969, Likens 1972) devoted to this issue. Before I summarize the result of this debate, I will continue with a description of the pattern of public response to environmental issues.

After this peak in awareness, debate, reaction, and increased study, the environmental issue advances to a stage (Fig. 52) where either the public gets tired of it and it fades away unresolved (boredom/apathy), or scientists produce a breakthrough that makes it so clear to everyone that there is no longer any argument about what needs to be done, or more likely it becomes politically expedient or economically advantageous to "solve" the problem, and it goes away, at least in terms of news coverage and public awareness.

The role of chlorofluorocarbons (CFC's) in the destruction of stratospheric ozone is another good example of this pattern (Brodeur 1986, Rowland 1989). The "problem" was identified clearly in the mid 1970's (Molina and Rowland 1974, Rowland and Molina 1975). Molina and Rowland's predictions about the serious destruction of ozone in the stratosphere by CFC's led to a ban, effective in the US in 1978, on CFC's as aerosol propellants. The urgency and severity of the problem was discounted by many scientists and particularly by industry. For example, the Du Pont Corporation actively and aggressively opposed any restrictions on the production of CFC's because the ozone destruction theory had not been "proven." As a result, additional proposed regulations on CFC's in the US were abandoned in 1981. The discovery and reporting of the Antarctic ozone hole in the mid 1980's (Farman et al. 1985) sparked a new surge of public awareness and concern. That finding led rapidly to the signing of a United Nations Environment

Program convention in 1985 and a multi-nation protocol in 1987 to restrict emissions of CFC's to protect the stratospheric ozone layer (Cicerone 1989, Rowland 1989).

The financial stakes for industry are relatively low for CFC reduction or elimination, i.e. CFC's represent a small (about 2%) part of Du Pont's (the major producer of CFC's) total revenues and few jobs appear threatened. Any losses may be reduced "...by the windfall profits to be earned on the dwindling supply of the chemical" (Shea 1988). Also, it appears that Du Pont's opposition to controls on the production of CFC's may have eased at the same time they were announcing a substitute for CFC's. This situation contrasts with midwestern US utilities who cite ratepayers and coalminers as being hurt seriously when emissions of SO₂ are controlled.

In the phosphorus/eutrophication and stratospheric ozone issues, it appears that science was important in resolving the issue, although I am not certain. Certainly as a result of the controversies that were generated, there was an increase in availability of funds for scientific research and a spurt in research activity. For example, a team of scientists initiated studies in 1968 to experimentally manipulate the nutrient content of lakes within the Experimental Lakes Area (ELA) of Canada. D. W. Schindler and colleagues published three significant and visible papers in *Science*, reporting the results of some of these experimental studies at the ELA (Schindler et al. 1972, Schindler 1974, 1977). They showed (1972) that carbon dioxide input from the atmosphere was sufficient to prevent carbon limitation of phytoplankton growth. Schindler also showed (1974, 1977) that phosphorus normally is the critical element controlling algal growth in fresh waters, something that limnologists had believed for at least forty years, but these whole-lake experiments showed it clearly.

At about the same time W. T. Edmondson (1969, 1970, 1972a, b) reported in a highly visible study through a series of scientific papers, including one in *Science*, that following diversion of phosphorus-rich sewage effluents away from Lake Washington in Seattle, Washington (USA), the lake had recovered quickly (to pre-1950 levels) from excessive eutrophication (see also p. 57 ff.). Sewage diversion was initiated in 1963 and completed in 1968. Edmondson identified phosphorus in wastewater as the major controlling factor in the eutrophication of Lake Washington.

These scientific papers, an earlier O.E.C.D. report by Vollenweider (1968) and activities and reports from the IJC that were influenced by Valentyne seemed to provide the basis to develop new legislation in the US and Canada for limiting the release of phosphorus to the environment, as

well as for the reformulation of detergents into phosphorus-limited or phosphorus-free types in an attempt to reduce eutrophication. As a result, laundry detergents in New York State, for example, currently contain no phosphates.

Clearly, input of scientific information is fundamentally important to decision making, but I am not convinced that science frequently plays the *decisive* role in political decision making relative to environmental issues in the United States. In any event, the linkage of scientific information to decision making is not strong. We held a workshop at the Institute of Ecosystem Studies in 1984, bringing together policymakers and scientists to debate the question, "Does scientific information really matter in policy decisions?" The scientists were pessimistic, but the policymakers were less so. At the end of the meeting, we focused on acid rain and asked the question, "Is there a scientific consensus on acid rain?" If there were a consensus, then it would be a basis for decision making. Of course, there are other major factors in policy decisions, in particular, political and economic considerations. We selected six major governmental reports on acid rain that had been prepared by scientists. We generated fundamental questions about the issue and then looked for the answers in these six reports. We copied verbatim the "answers" from the federal reports (Driscoll et al. 1985). We then distributed our findings ("Is there scientific consensus on acid rain?") widely to politicians, colleagues, and the news media. In fact, these federal reports, including one commissioned by the Reagan Administration's Office of Science and Technology Policy (OSTP), all showed considerable consensus. Indeed, the President's Acid Rain Peer Review Panel of OSTP recommended (1984) "... that additional steps should be taken now which will result in meaningful reductions in the emissions of sulfur compounds into the atmosphere. . . . The overall scientific understanding of the various aspects of acidic precipitation is incomplete at the present time, and will continue to have major uncertainties well into the future. . . . For these reasons, any current scientifically-derived recommendations must be based on an imperfect, always increasing, body of pertinent data whose quality and completeness can be expected to improve for decades. Recommendations based on imperfect data run the risk of being in error; recommendations for inaction pending collection of all the desirable data entail even greater risk of damage." Nevertheless, our effort to summarize the scientific understanding and to report on consensus had little apparent impact on the acid rain issue in the United States. The political decision was to continue study of the problem.

Often the public is ahead of science regarding action on environmental issues. The public usually wants to know what the scientific facts are, but is impatient for action. Also lag time following the development of scientific understanding and political action may be long (Fig. 52).

There is an even more frustrating example. Ten years ago, who would have predicted that the United States would spend over \$570 million on a scientific assessment of the acid rain issue, and then that Congress would pass legislation on this issue without waiting for the final report from this assessment. That is just what happened! During spring of 1990 both the US Senate and the House of Representatives overwhelmingly passed amendments to the Clean Air Act, including provisions to control acid rain, and then in November 1990, President Bush signed this legislative bill without waiting for the final report from the National Acid Precipitation Assessment Program (NAPAP), which was due in December 1990. The linkage between science and the formulation of public policy regarding environmental problems in the United States is not good. We must do better in the future, particularly regarding extremely complex, multifaceted problems, such as global climate change (see p. 127 ff.).

From 1980 to 1988 the Reagan Administration opposed consistently any regulatory action to reduce acid rain, again citing a "need" for more information. For example, Kathleen M. Bennett, Assistant Administrator for Air, Noise and Radiation of the US Environmental Protection Agency, testified in February 1982 at a hearing of the Senate Environment and Public Works Committee, "Within two or three years, we expect to have some very important findings that will help guide us. It is possible that those will suggest further activities that are necessary, and it is possible that they won't." It was much less expensive for the federal government to spend some \$50 million per year to *study* the problem than it would have cost to *regulate* the problem. Study clearly was a less expensive alternative, both in terms of monetary cost and in terms of political risk for addressing this controversial, environmental issue.

Early during the Bush Administration in 1989, however, the President, Secretary of State James Baker, and Administrator of the US Environmental Protection Agency William Reilly, all identified acid rain as a priority issue needing resolution. Most noteworthy, however, was the replacement in 1989 of Senator Robert C. Byrd by Senator George J. Mitchell as Majority Leader of the US Senate. Senator Byrd of West Virginia (a coal-mining state) consistently had fought any acid rain legislation, whereas Mitchell of Maine (a state geologically predisposed to damage from acidification) had

sponsored several legislative proposals. A legitimate question to ask relative to the topic considered here, then, is: “What scientific finding occurred in 1988–1989 to cause this sudden turnaround in the political climate related to acid rain?”

The National Academy of Sciences/National Research Council had produced several important reports relating to acid rain during the 1980’s (Schindler 1981, Calvert 1983, Norton 1984, Gibson 1986). Nevertheless, the Academy had been either quiet or a relatively conservative voice during the political debate regarding the need for controls on acid rain during 1980–88. “Suddenly” in autumn 1988, the National Academy of Sciences produced jointly with the National Academy of Engineering and the Institute of Medicine a “position paper” for the Bush transition team that called for action on acid rain. They stated, “. . . there are political and economic components in any decision on dealing with acid deposition; and to date such decisions have been deferred by the past two Administrations in favor of more research. We believe that the sources of acid deposition, the technology to limit emissions, and the associated costs and political risks are now sufficiently understood that further deferral in favor of more analysis is unwarranted” (Anonymous 1988, p. 3-4). In my opinion, there were no *major scientific breakthroughs* relative to acid rain during this period that would justify these “sudden” political actions to resolve this environmental problem (see also p. 127 ff.). The basic understanding about the effects of acid rain that had been generated by about 1980, primarily from studies of aquatic ecosystems and largely from research done in Europe, was not significantly changed by NAPAP (see also Loucks 1992). It was this earlier understanding, by and large, that was the basis for the public’s outcry against acid rain and for the politician’s response.

Scientific Communication and the News Media

During the recent hot, dry and polluted summer of 1988 in North America, numerous articles about the environment appeared in the news media. A major article in *The Boston Globe* appeared on 14 July 1988, and described various environmental problems related to acid rain, particularly those in Canada. As is well known, pictures are important for attracting attention. Although there was little in this article about lakes, the *Globe* used a picture about a scientist collecting water samples. The caption read, “Tony Blouin of Dalhousie University, Halifax, Nova Scotia, demonstrates

the Van Dorn sampler, which collects lake algae that are later analyzed for levels of acidity.” Of course, such measurements of acidity are not done, nor would they be helpful. The caption was just plain wrong, and the picture was not particularly pertinent to the article anyway.

Another article appeared one week later on the front page of *The New York Times*. Again, to capture attention, there was a dramatic picture of a forest of dead trees. All the trees in the picture looked dreadful and provided a frightening illustration. The caption read: “Dead trees on Mt. Mitchell in North Carolina, which was covered with red spruce five years ago.” Unfortunately, the trees weren’t red spruce (*Picea rubens*), and they may not have been killed by air pollutants, which was the main topic of the article.

The question that I’m raising is complicated and somewhat emotional. These news reports are highly visible, but they contained serious mistakes, and such mistakes are common in the news media. Are these mistakes important? Is it permissible to tell “little white lies” (e.g. the fish skeletons mentioned on p. 109) in order to achieve a “valuable” result? Of course, scientists can make errors in their publications as well, but a primary tenet of the scientific method calls for a critical re-testing and re-examining of results and conclusions in a self-correcting process. The political and ethical considerations relative to scientific publications have been and are being discussed widely elsewhere (e.g. Medawar 1979, Janovy 1985, Booth 1989, Jaroff 1991) and are beyond the scope being addressed here. Also I want to differentiate clearly here between fraud and little white lies.

I would like to share some questions that may be at the crux of this problem in reporting scientific information. These questions relate to ethical behavior, sustained scientific research and formulation of public policy. First, do scientists have an ethical obligation to make their research results known to the public? My answer would be an immediate “of course”! Most research in the United States is funded by taxpayers, and we scientists have an obligation to report our results and to inform the “public.” Of course, we must publish, but does this mean publish only in peer-reviewed journals? I have stressed earlier the value of publishing in peer-reviewed journals to establish scientific credibility. Is that where our ethical obligation ends? What is a peer-reviewed journal? Does this mean only that a “peer” must have seen the paper and made comments about it? My favorite examples for the type of review comments that scientists sometime receive are – “Great article. Publish it.” Or, “Excellent proposal – wish I had time to read it”! I have received reviews like – “I didn’t like it.” Nothing more. Were these peer reviews? If so, they weren’t helpful in improving the product. Fortu-

nately, most scientific reviews are thoughtful and helpful. Scientific peer review has been (e.g. Marshall 1989) and will be criticized, but it represents the best option that we have for achieving uniformly high quality in scientific research. A proper peer review is one where there is an opportunity to *reject* the article if it doesn't meet clearly stated standards, but frequently this option is not normally practiced in large, federally sponsored studies that produce reports.

Although comprehensive and laborious, the so-called "peer review process" in many federally sponsored studies is very different from the norm expected in science. For example, realistically, there is no real option for rejection of reports from these studies. Reports must emerge at a specified time and usually in a specified format. But these requirements mean that the process is fatally flawed from a scientific point of view. It is not possible to *buy* full and complete answers to complex environmental problems within a *specified* period of time. The customary quality review process for science – publications in peer-reviewed journals – is largely bypassed because of time constraints, sheer volume and nature of the assessment. The result can lead to poor scientific communication as applied to complex environmental questions (see p. 127 ff.).

Another important question relative to communication of science is, should scientists talk to reporters? If scientists have an obligation to make their results known to the public, what better way is there to make results known to the public than to talk to reporters? A recent survey (HRN 1990) indicated that leaders in US business, government, education and other areas relied on major national newspapers more than any other source for information about environmental issues. Admittedly, I have used the news media as a convenient source of some information cited in this book.

Most scientists probably would agree that they have an obligation to inform the public about their research findings. Why then wait until findings appear in technical language in a peer-reviewed journal and hope that an intelligent and curious reporter will choose to interpret them to the public? Why not go directly to the public via the news media? We might save a life or we might save a lake. Why then are scientists reluctant or afraid to talk with reporters?

Scientists frequently are misquoted or misunderstood by reporters and are embarrassed by subsequent news accounts. Then their peers respond, "Why did Likens say that? He ought to know better! Is he that stupid?" When your peers have that impression, how do you think one fares when it is time to be evaluated for promotion or for salary increase? Indeed, being

quoted on the front page of *The New York Times* may not be an advantage to a scientist at such times, particularly to a young scientist. As a result, many scientists are very hesitant about talking to reporters at all. During the autumn of 1987 the NAPAP produced a controversial Interim Assessment (Kulp 1987). I was called by a number of prominent science reporters, and each one of them complained bitterly to me that most other scientists would not talk with them. I asked why, and the reporters said that the scientists had said that they were afraid they might lose their jobs or their research funds if they talked to reporters on this highly politicized topic. Why do some scientific peers frown on colleagues for talking to reporters, and some university and particularly governmental administrators attempt to control or even forbid their scientists from talking to reporters?

Scientists know how the standards of quality control are applied in scientific journals. Our best journals and the majority of our grant proposals are peer-reviewed fairly and intelligently with an opportunity to reject. How is quality controlled by the news media? What if I wrote a report indicating that I had discovered a new cure for AIDS, and I carried it to the editorial offices of *The New York Times* and said, "Here, you should publish this tomorrow on the front page; this is an important finding!" Obviously, they wouldn't publish it, or at least I hope they wouldn't. Why then was the story about bird droppings being a major source of acid "rain", which was not peer reviewed, printed in about every newspaper in the country, including on many front pages? How does the news media determine if stories from a reporter or supposed scientific "expert" are valid? A recent and visible example is provided by the unfounded predictions by a self-taught climatologist, that a major earthquake would strike the Mississippi Valley of the US, during the first week of December 1990. These "findings" were reported widely in the news media and caused much public hysteria. Upon investigation, this scientist was found to be neither an expert on earthquakes nor scientifically qualified to make such predictions (Kerr 1991). Why did the press listen and believe?

How do we determine whether news stories are scientifically accurate? Is there a difference between being scientifically important and being newsworthy? Who determines? A. Fauci, Director of the National Institute of Allergy and Infectious Disease and coordinator of AIDS research at the National Institutes of Health, has stated, "The media are no place for amateurs I remember the sinking feeling . . . when a writer asked me how to spell 'retrovirus'. . . . Someone who does not know that . . . should automatically be disqualified from doing an AIDS story" (Fauci 1989).

How do we reach consensus in science – if a report says so, or if it appears in *Science*, or if it appears on the front page of *The New York Times*? If an article were to appear in *The New England Journal of Medicine*, and then be reported in *The New York Times*, one might think that it represented a consensus. Sometimes it is stated, “Most scientists believe ‘so and so’.” What does anyone know about what “most” scientists believe? The public and policymakers often are confused by diverging reports from scientists. Different scientific interpretations are common, in fact expected, in the self-correcting scientific process, particularly in extremely complex issues such as those related to environmental questions. The media, particularly inexperienced or poorly trained reporters, frequently give equal weight to common scientific understanding and to radically divergent views or to views from vested interests, without clearly describing the background of the interpretation being reported. Reporting limits, statistical or otherwise, on scientific findings and their application would provide much needed information to the intelligent consumer of scientific facts in the public news media.

These are important questions relative to multifaceted environmental problems with so much at stake. We need to derive and to apply the answers.

And finally, a major ethical question: Can any answer be purchased? Many believe that scientific “answers” are for hire. If so, that shiny armor becomes tarnished very quickly.

Recently I had a very disquieting experience in this regard. I was invited to meet with representatives of one of the largest coal companies in the United States. During the course of the meeting the representatives from the coal company admitted that their company had hired a “. . . whole roomful of Ph.D. scientists to obfuscate, confuse and delay at every opportunity. . .” the acid rain issue and its regulation. I was shocked and asked, “. . . but who then cares about the human condition?” Their response was, “. . . we do, but we must maintain this activity if we are to sell our coal to the electrical utilities, who oppose any regulation.”

At the moment, the global climate change issue has politicians and scientists throughout the whole world in turmoil. How are we going to make decisions about such difficult environmental issues? How can we inform the public about these issues? How do we make decisions about important environmental matters where there are vast sums of money at stake? It’s clear that there will be major environmental problems ahead. How do we make accurate information available to the public, including politicians, so that they will understand it and be able to develop wise policies and take intelligent action based on it?

Whose responsibility is it to deal with the numerous complicated problems related to environmental issues?

- (1) Reporters and editors must take the time to get it right! Dianne Dumanoski, a science writer for *The Boston Globe*, is a model in this regard. The news media should make the effort to hire and develop specialists to report about complicated scientific subjects.
- (2) Scientists must work with reporters to disseminate new findings and to make them clear and understandable to the public. Scientists must be certain that uncertainties are understood. Some simple, but useful suggestions to help “get it right” are made both to reporters and to scientists in an article by Warner et al. (1991).
- (3) Emitters/releasers must stop irresponsible corporate decisions and actions, which only attempt to maximize profits, and instead accept roles of social responsibility and leadership.
- (4) Politicians must provide leadership and form partnerships with the public to make it easier for individuals to accept responsibility about environmental issues.
- (5) Students must learn more about environmental issues and ethics in order to develop a “meaningful philosophy of life” (Astin et al. 1987). Current trends in attitudes of young adults toward more selfish and materialistic goals are worrisome from this point of view (Bailey 1990). Students also must learn how to write and speak clearly; such communication is an integral part of doing scientific research (Kinne 1988).
- (6) Teachers must provide a balanced discussion of environmental issues, using real-world examples.
 - “... universities should be among the first to reaffirm the importance of basic values, such as honesty, promise-keeping, free expression and nonviolence, for these are not only principles essential to civilized society; they are values on which all learning and discovery ultimately depend” (Bok 1988, p. 31).
 - There should be increased course offerings about the relationship between ethics and environment, and there should be requirements of students to take them.
- (7) Individuals must accept responsibility for their part in these problems, and take the time to learn about their environment. We must conserve, recycle, and be efficient; all of which will reduce waste.

Thus, I believe that each of us has a role in society in resolving environmental problems. Each of us has an ethical obligation to be responsible and to do our part in protecting and maintaining a healthy environment. Such shared responsibilities are a central tenet for environmental ethics.

The costs for environmental protection are quite large, but are insignificant relative to the expenditures that nations of the world make for their military "security" (Table 13). What are our priorities for spending? How are these priorities established? What can we afford in the future? I would argue that science, ethics and an enlightened public are critical components in developing wise answers to such questions, which are critical to the survival of human societies.

Table 13. Spending on military vs environmental security. Human populations worldwide spent over $\$ 900 \times 10^9$ on military purposes in 1985, more than $\$ 2.5 \times 10^9 \text{ d}^{-1}$. (From Brundtland 1987; modified and expanded)

Environmental problems	Cost to ameliorate ($\$ \times 10^9 \text{ yr}^{-1}$)	Equivalent military expenditure (Days)
Action plan for tropical forests	1.3	0.5
Lack of clean water in Third World	30	10
Acid rain – halving emissions of SO_2 and NO_x		
– Eastern USA	6	2
– Europe EEC	5–7	3

Concluding Remarks. *It is indeed tempting to close on a pessimistic note. Much of what sustained ecological research has revealed is a relentless degradation of the global environment. It is impossible to pick up a major daily newspaper without learning of some new environmental assault or additional evidence of slow deterioration. Much of this is not "news" to ecologists, particularly to ecosystem ecologists.*

So while I have been critical of the quality of reporting on subjects that I know about, I am compelled to acknowledge that these subjects are at

least being put before the public. Acid rain, the stratospheric ozone hole, tropical deforestation, global climate change, toxic wastes, ocean dumping, eutrophication – who would have thought a few years ago that these topics would compete successfully for space on the front pages of our major newspapers? On the other hand, why have we permitted ourselves to be so destructive of our very life support systems (natural aquatic and terrestrial ecosystems) so that our actions now make front page news?

Philosophers embracing utilitarianism say that good actions are those that promote the greatest benefits for the greatest number of people. This concept seems particularly difficult for political leaders or Corporate Executive Officers (CEO's) to take seriously unless they modify it slightly – the greatest good for the greatest number of voters in my district, or holders of my company's stock. If – and this is a big “if” – those in positions of power would look beyond greedy, short-term profits or beyond the next election, they could be forced to think about who is responsible for environmental problems. This thought process may prompt them to accept responsibility and action which benefits those who live downstream (Fig. 54). We all need a renewed sense of individual responsibility. Such a sense of responsibility is vital for humans to manage, diminish and attempt to prevent such enormously complex environmental problems.



Fig. 54. Cartoon: "Toxic Fumes – Formally [sic] Sea Breezes" (From *Science* 239(4841): 791, 1988)

(3) Ecology, Ecosystems and Environmentalism

“With man, most of his
misfortunes are occasioned by man.”

Pliny the Elder
23–79 A.D.

“Big” Science – The National Acid Precipitation Assessment Program

Increasing awareness of the severity of widespread environmental problems is forcing ecosystem science increasingly to respond to offers of large amounts of money for directed, problem-orientated research, to deadlines for “completion”, and to the “need” for answers to policy questions. The recent major government-supported programs related to acid rain in Europe and North America are excellent examples. The United States in 1990 completed 10 years of a National Acid Precipitation Assessment Program (NAPAP). More than \$570 million were spent on NAPAP during this decade.

The NAPAP was faced with a multifaceted, complex environmental problem, and had to deal with many forces (e.g. scientific, political, bureaucratic) that were pulling at it from all sides. I have been critical of the assessment conducted by NAPAP, particularly of the way in which statements in the executive summary of an Interim Report from NAPAP in 1987 (Kulp 1987) were unsupported by scientific evidence. Likewise, Dr. James Mahoney, NAPAP’s Director during 1987–1990, stated in interviews with the news media near the end of the Program that acid deposition causes problems, but the impacts are not as destructive as “some” had predicted earlier (Roberts 1991). In contrast, it has been argued that the problem is greater than was suggested in 1972 (Bormann and Likens 1987). Not only was the science in NAPAP complex, but explanations to managers, decision makers, and the public often were not clear or straightforward. The real and potential effects of air pollutants on natural ecosystems are complicated (e.g. Likens 1989b). For example, the effects of air pollutants on forested ecosystems of Whiteface Mountain in the Adirondack Mt. region of New York State have been studied extensively (e.g. Scott et al. 1984). It has been found that more than 70% of the red spruce trees (*Picea rubens*) either have

been killed or seriously damaged by air pollution in combination with natural stresses. However, near the summit of Whiteface Mountain are strips of dead fir trees (*Abies balsamea*) that are part of natural fir “waves” (Sprugel and Bormann 1981). From a distant vista it is difficult to determine which “damage” is natural and which is anthropogenic. Such complex interrelationships are not easy to explain to a lay audience.

Another example of this complexity is provided by our study of the historical acidification of lake ecosystems in the Adirondack Mt. region (Asbury et al. 1989). To evaluate the extent to which acid rain had affected surface water chemistry, my colleagues and I compared chemical data that had been collected in the 1930’s with current data for 274 lakes where such data exist. We found that about 80% of these lakes became more acid during this period (Asbury et al. 1989). However, lakes changed in a variable fashion and some of the lakes even became more alkaline (Fig. 55). This result is not surprising scientifically because these lakes respond individually to a widespread pollutant, such as acid rain (e.g. Likens 1992a). But to explain such complexity to decision makers and to the public is difficult.

The NAPAP effort was “big” science on a forced march, with platoons of consultants, civil servants and scientists stepping to the cadence of a federal bureaucracy. Reports were supposed to emerge at specified times. My eval-

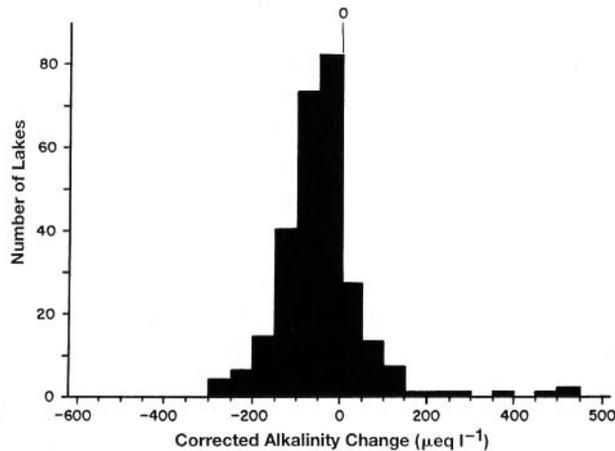


Fig. 55. Frequency distribution of changes in alkalinity between surveys done from 1929 to 1934 and surveys from 1975 to 1985 for 274 lakes in the Adirondack Mountain region of New York State. These data were corrected for methyl orange over-titration. (From Asbury et al. 1989; modified)

uation of NAPAP should not be interpreted as being critical of the NAPAP scientists or their science. Indeed, their efforts contributed significantly to an understanding about acid rain and air pollution. The expenditure of some \$570 million dollars supported much new research as well as synthesis of existing information. Instead, I am critical of the organization and process whereby the scientific assessment was done. For example, the NAPAP *reports* are analogous to student term papers on an assigned topic where the grades can range from A (= excellent) to F (= failure). Yet unlike publication in peer-reviewed journals, there was no real option in the NAPAP effort to “fail” poor efforts and reject their publication (i.e. grade of F). Although many scientific papers were published, the customary quality review process for science – publication in peer-reviewed journals (see p. 118 ff.) – was largely by-passed by the Program because of time constraints, sheer volume and “need” for “answers”. The result was voluminous interim reports combined with compact “sound bites” and easily digested headlines for the news media, such as “Worst Fears on Acid Rain Unrealized” (*The New York Times*; Roberts 1991) appearing just in time for the closed-door congressional debates on clean-air legislation.

Notwithstanding, both the US House of Representatives and the US Senate overwhelmingly passed Amendments to the 1970 Clean Air Act during the spring of 1990, including specific provisions to regulate acid rain. President Bush signed these amendments to the Clean Air Act of 1970 into law (Public Law 101-549) in November 1990 without waiting for the final NAPAP report, which was due in December 1990. NAPAP’s final report exceeded 6000 pages! It might be argued that Congress and the Executive branch of government were well briefed by NAPAP and, therefore, the availability of a final report didn’t matter. This procedure, however, makes a mockery of the scientific peer-review process. And, who was being briefed and who was doing the briefing? Is this successful “big science” as applied to decision making for complex environmental questions? I think not. One prominent staff person in the US House of Representatives, speaking at a national meeting of The American Institute of Biological Sciences in August 1990, stated that “NAPAP was politically irrelevant” regarding legislative approval of Amendments to the 1970 Clean Air Act (M. Rode-meyer, pers. comm.).

NAPAP was formulated as an assessment program and designed to issue regular “assessments”. Although annual reports about the Program were produced, starting in 1982, assessments were lacking. According to the US General Accounting Office, through fiscal year 1985 NAPAP had spent

\$6.7 million in developing assessments but no assessments had been published. Obviously better assessments were needed, and we desperately need better linkages between science, scientific assessments and policy decisions related to complex environmental problems.

Now that an Amendment to the 1970 Clean Air Act has been enacted to regulate acid rain, it is reasonable to ask, will this legislation protect sensitive ecological systems? These amendments call for a reduction of 10 million tons (9.1 million metric tons) in SO_2 emissions below the 1980 levels by the year 2000 (Fig. 56). Actual reduction in the emissions of SO_2 will be accomplished by counting one million tons (0.9 million metric tons) for the reduction that already has occurred since 1980. An additional 9 million tons (8.2 million metric tons) would be gained by limiting emissions from electrical power generating plants, smelters, and other sources. Prior to the Amendment it was projected that emissions of SO_2 would increase to the year 2000 and somewhat beyond (Streets and Veselka 1987). Thus, the effective reduction caused by the Amendment to the Clean Air Act is appreciably more than 10 million tons (9.1 million metric tons). While this is a good step forward, a major problem with the legislation is that it lacks a strong provision to significantly reduce emissions of nitrogen oxides. Nitrogen oxides contribute to nitric acid, a major component of acid rain in the US and Europe (e.g. Likens et al. 1979, Galloway and Likens 1981, Likens 1985a). The law requires a reduction of 2 million tons (1.8 million metric tons) of nitrogen oxides from 1980 levels by the year 2000.

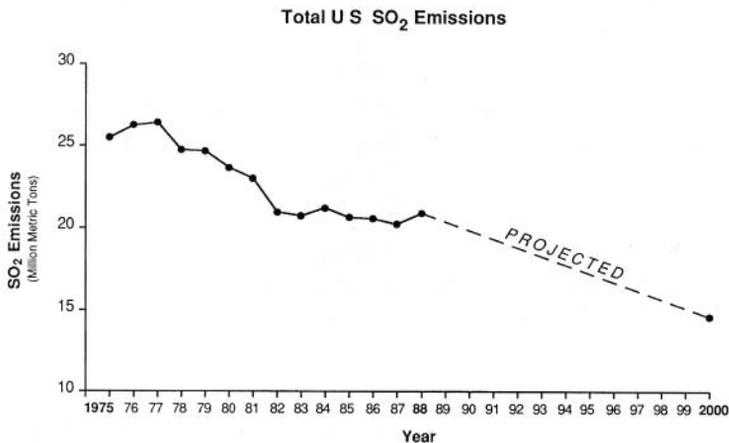


Fig. 56. Total SO_2 emissions for the United States from 1975 to 1988 and projected to the year 2000, based on 1990 Amendments to the Clean Air Act

Using long-term data from Hubbard Brook, federally mandated changes in emissions, and a regression relationship between emissions of SO₂ in the eastern US and wet deposition at Hubbard Brook, I have estimated the total (wet plus dry) deposition of sulfur at Hubbard Brook in the year 2000. Concentrations of SO₄⁻ in precipitation, as well as SO₄⁻ deposition, have been decreasing at Hubbard Brook since the early 1970's (Fig. 17), and these changes have been related to changes in emissions of SO₂ in the eastern US (Fig. 57; Likens et al. 1984, Hedin et al. 1987, Butler and Likens 1991; p. 41 ff.). Obviously, deposition is the product of chemical concentration times the amount of water, so it is important to determine whether there was a significant trend in the amount of precipitation (Fig. 7) from 1964 to 1990 or for shorter periods, that could produce a misleading correlation with the decline in emissions of SO₂. There was no statistically significant ($p < 0.05$) trend in amount of precipitation at Hubbard Brook for either the entire period or for 1970 to the present or for 1973 to the present. Thus, it appears that decreasing sulfate concentration was the major factor in causing the decline in sulfate deposition at Hubbard Brook from 1964 to 1990.

The statistically significant ($p < 0.01$) relation between SO₂ emissions and SO₄⁻ deposition at Hubbard Brook is $Y = -308 + 51.1 X$ ($r^2 = 0.70$),

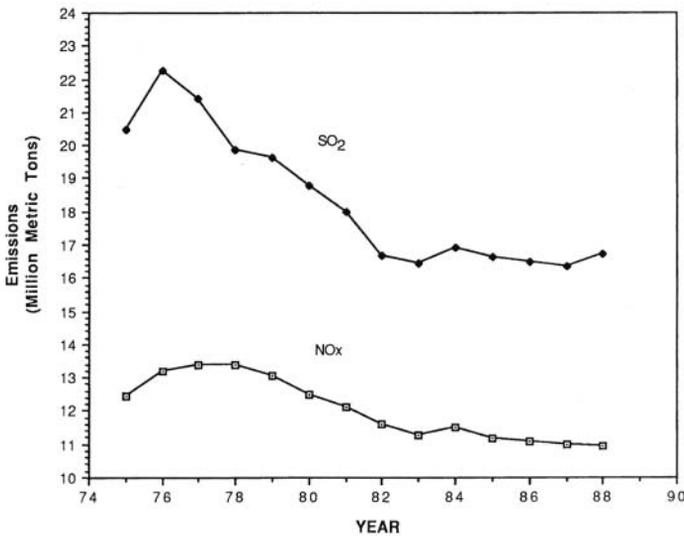


Fig. 57. Emissions of SO₂ for the eastern US from 1975 to 1988. The area contributing these emissions is assumed to be the appropriate source area for the Hubbard Brook Experimental Forest (Butler and Likens 1991). (Data from Kohout et al. 1990 and pers. comm.)

where $Y = \text{SO}_4^-$ deposition in eq/ha-yr and $X = \text{SO}_2$ emissions in metric tons yr^{-1} (Fig. 58). This relation of sulfate deposition to emissions of SO_2 was used to extrapolate the long-term record of SO_4^- deposition at Hubbard Brook to the year 2000 (Fig. 59). Also shown in Fig. 59 is a straight-line extrapolation of the long-term record of sulfate deposition to the year 2000. Because these extrapolations represent wet deposition only (sulfate concentrations in bulk precipitation samples at Hubbard Brook approximate wet-only values; see Driscoll et al. 1989a), an estimate of dry deposition, equivalent to 50% of the long-term average (Likens et al. 1990b) dry deposition value at Hubbard Brook, is added at year 2000.

Considering both of these scenarios for projecting wet and dry deposition of sulfate at Hubbard Brook to the year 2000 (Fig. 59), the estimated sulfur loading from the atmosphere will still be 2.7 to 3.3 times higher than values recommended for protection of sensitive forest and associated aquatic ecosystems like those found at Hubbard Brook. In fact, projected total deposition of sulfate at Hubbard Brook for the year 2000 is similar to the wet deposition value in 1980. (It was these wet deposition values that

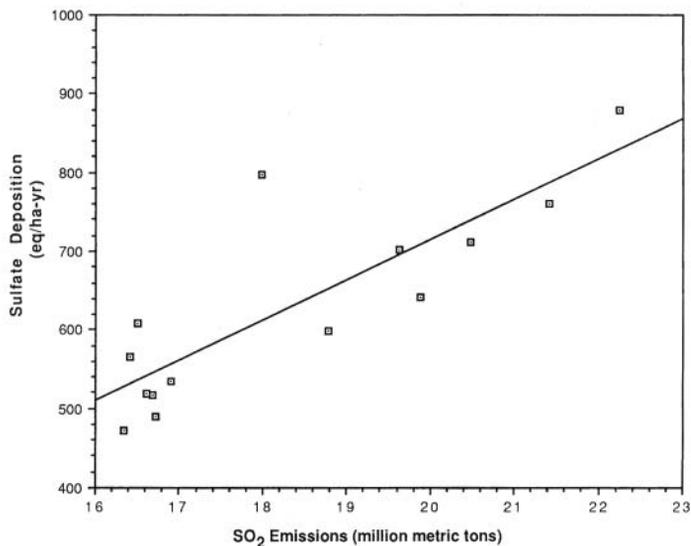


Fig. 58. Relation between calendar-year SO_2 emissions in the eastern US (Fig. 57) and calendar-year SO_4^- wet deposition at Hubbard Brook. The regression line has a probability for a larger F -value of <0.001 and an r^2 of 0.70

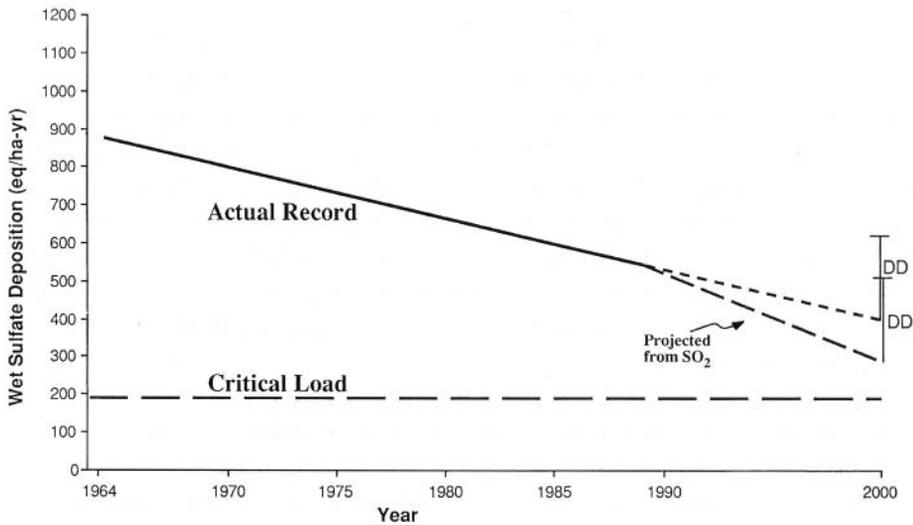


Fig. 59. Wet deposition of sulfate for Watershed 6 of the Hubbard Brook Experimental Forest between 1964–65 and 1989–90 based on regression analysis (——). Projections to the year 2000 are based on (1) regression relationship for historical changes in SO₂ emissions from 1975–1988 and wet SO₄⁻ deposition (Fig. 58) (— —); (2) a straight-line extrapolation of the long-term record of SO₄⁻ wet deposition at Hubbard Brook (----). DD = dry deposition of sulfate (Likens et al. 1990b). See text for further explanation. (Critical level based on Nilsson and Grennfelt 1988)

were judged by decision makers to be unacceptably high, and, therefore, were the primary justification for reducing emissions of SO₂.) Moreover, declining atmospheric inputs of base cations at Hubbard Brook (Figs. 20 and 21) apparently are causing forest and associated aquatic ecosystems at Hubbard Brook to become even more sensitive to atmospheric inputs of acidic substances (Driscoll et al. 1989a; p. 45 ff.). The so-called “critical load” (Fig. 59) is defined as “the highest deposition of anions corresponding to strong acids that will not cause chemical changes leading to long-term harmful effects on essential ecosystem properties” (Nilsson and Grennfelt 1988). Thus, although the amendments to the Clean Air Act should produce improvement, it appears that reductions in emissions of SO₂ will not be large enough to accomplish the desired goal.

In my opinion, provisions are also inadequate in the Amendments to the Clean Air Act for monitoring progress on how well we will do after implementation of the legislation fully goes into effect, probably around the year 2000. It frequently is typical of politically generated management solutions to pass a law and then forget about the problem. Unfortunately, environ-

mental problems like acid rain do not go away this easily. It will be important to determine whether the legislation has been effective; whether emissions have been reduced enough to protect sensitive natural ecosystems; or whether emissions have been reduced by too much, and thus money is being wasted. The only way to find answers to these important questions is to monitor the air-land-water system for a long time (see p. 27 ff.). It could be argued convincingly that there would have been little controversy about the acid rain issue if long-term (e.g. 50 yr) monitoring data were available. Not only is such monitoring prudent ecologically, but it is prudent economically.

I believe that NAPAP also was fatally flawed as an assessment because of its legislatively determined premise that answers, useful to policymakers, could be purchased by a specified time given enough expenditure of money. Obviously, from a scientific point of view, it is naive and unrealistic to believe that all of the assessment answers for such a complex environmental problem will be available just because the time allotted for some government-directed program has expired. This "need" for scientific answers is simultaneously both a major driving force for initiation and funding of large, bureaucratic programs and a dilemma to scientists faced with the reality of integrating natural variability with the deliberate scientific process.

It is extremely difficult to suggest improvements in this process in the future, especially considering even more complex political and ecological problems associated with developing environmental issues, such as global climate change. The scientific, economic, political and sociological aspects of the climate change issue are mind-boggling. Nevertheless, in my opinion, the following components should be included in an *assessment* program for large, multifaceted environmental problems, such as global climate change: (1) Focus should be on an assessment of environmental risks, as well as benefits of mitigation, with annual, or similarly regular assessment reports, to the primary legislative body of the governmental entity (e.g. US Congress). [NAPAP reported through a consortium of federal agencies.] The reports should be prepared for policymakers in an understandable manner, with uncertainties clearly stated. (2) A partnership (see p. 27 ff.) between policymakers and scientists should be forged, in which the best answers at the time are used to develop policy, but where the policy is modified iteratively as new information becomes available, possibly on 3- to 5-yr intervals. (3) There must be a strong and respected *science* program advisor to the executive officer of the government (e.g. to the US

President). (4) There must be a strong, practicing scientist to direct government-sponsored assessment programs, with authority to lead the program and to be evaluated by the scientific community on the basis of that leadership. This person must understand assessment needs and be adept at forging partnerships (#2 above). (5) The program should be led by ideas and questions relative to assessment needs, not by funding availability and top-down bureaucracy (i.e. science by committee); critical questions must be identified whose answers will lead to sound assessment and policy decision making. (6) A significant percentage (e.g. 15 to 20%) of the funds for an assessment program should be devoted to competitive, investigator-initiated, innovative research pertinent to the environmental issue. (7) A significant amount of the research results must be published in a timely fashion in peer-reviewed journals to evaluate and establish scientific credibility. (8) Regular scientific meetings with the international scientific community should be held to exchange information and to develop and evaluate an international scientific consensus.

Many of these recommendations may be difficult to implement, but in my opinion, the old NAPAP system was not successful given its level of funding. These recommendations provide a fresh start for assessing these problems. Each of the recommendations proposed above could and should be discussed and debated extensively. The political, economic and ecologic stakes are high.

The recommendation for active and iterative feedback between scientists and managers resulting in the development of a dynamic management program (#2 above) is critical to a successful assessment program, but will be disconcerting, if not threatening, to some corporate financial managers. Corporate managers frequently complain that new regulations cause redundant expense with short lead times for compliance, and do not allow for financial management of complex, mitigative actions. Hopefully, this new partnership in conjunction with close interaction with regulatory agencies would constantly address these problems even though some false starts are inevitable. When the arrangement becomes a true partnership with clear goals, then these frustrations would be minimized.

A fundamental premise for these suggestions is that scientific information and understanding are critical to an assessment and for making wise choices about the mitigation or management of a complex, environmental problem. Obviously, input from other disciplines (e.g. economics, sociology, ethics) would be required for a full assessment of the costs and benefits to society.

Human-Accelerated Environmental Change

I believe that scientists and policymakers should be focusing on a broader definition of global change instead of equating it solely with increases in greenhouse gases and global warming, as is currently so popular in the scientific and popular environmental literature. While global warming represents potentially one of the most serious threats ever faced by human societies, its effects on ecological systems may be difficult to discern against a background of other human-accelerated environmental changes (Likens 1991). Thus, I have proposed the term “*human-accelerated environmental change*” (Likens 1991) to describe a more encompassing effort regarding regional, continental and global environmental deterioration, and to focus clearly on the important human component. Many of these changes are occurring now over large areas.

Human-Accelerated Environmental Change includes, in addition to global climate change and ozone depletion in the stratosphere:

- (1) Land-use change, including fragmentation of landscapes from deforestation, urbanization, transportation uses, etc.
- (2) Toxification of the biosphere from air, land and water pollution, including acid rain, toxic metals, pesticides, etc. The costs associated with cleaning up or mitigating the toxic wastes from human activities are staggering. It has been estimated, for example, that it may cost as much as \$250 billion to clean up wastes at all of the US nuclear production facilities such as Rocky Flats, CO; Fernald, OH; Oak Ridge, TN; Savannah River, GA; and Hanford, WA.
- (3) Invasions of exotic species, for example, gypsy moth (*Porthetria dispar*), kudzu (*Pueraria lobata*), hemlock woolly adelgids (*Adelges tsugae*) and zebra mussels (*Dreissena polymorpha*), into natural ecosystems of North America. Obviously other countries, regions and continents have similar problems with increasing numbers of invading exotic species (e.g. Drake et al. 1989).
- (4) Loss of biotic diversity at the gene, species and ecosystem levels. Loss of biodiversity in the tropics and elsewhere is thought to have high rates currently because of human activity (e.g. Ehrlich and Wilson 1991).

The phrase “human-accelerated environmental change” puts an emphasis on the major role of humans in these environmental issues. The ever-

expanding human population throughout the globe, and its ever-expanding impact on the environment, cannot continue to be ignored. In fact, human population growth is the major accelerator for these environmental problems.

Ecosystem Science and the Future

Will the ecosystem approach be appropriate and useful in providing management solutions to large-scale environmental problems? I believe that it will be vital, because unless we stop addressing such complex problems in a fragmented way management actions will be piecemeal and often ineffectual. Seeking solutions for the environmental “crisis of the month” is neither cost-efficient nor effective in the long term.

The ecosystem concept has great value for developing sound management policies and for developing an understanding about linkages among systems within and among complex regional landscapes. Its value stems primarily from the integrated and comprehensive (incorporating abiotic and biotic factors) approach. Such an orientation is vital to address currently widespread human-accelerated environmental changes. The ecosystem approach has been especially valuable for understanding large-scale environmental problems, such as eutrophication of lakes, acid rain and fisheries management in the Laurentian Great Lakes. For example, the International Joint Commission (see p. 111 ff.) found the need to move from a water-quality approach to an ecosystem approach in the mid 1970’s because most of the environmental problems related to the Laurentian Great Lakes had major components in the watersheds or airsheds of these lakes.

So-called “new forestry” (Gillis 1990, Luoma 1990, Franklin 1992) and “urban to rural gradient ecology” (URGE; McDonnell and Pickett 1990) provide new approaches to forest or woodland management that rely heavily on the ecosystem concept. New forestry promotes the maintenance and management of complex forest ecosystems for timber production, as well as other societal benefits, such as storage of atmospheric carbon dioxide and habitat for endangered species. The URGE concept examines human impacts on ecosystem structure, function and development along a gradient of urban to rural habitats. Hopefully, the results of URGE will provide guidelines for managing urban green space that are based on an ever-changing, living, ecological system dominated by humans. Ecosystem science also provides a conceptual framework for evaluating the linkages between ecosystems imbedded within the matrix of a landscape or region, such

as forest, agricultural and urban habitats, and for addressing large-scale environmental problems and natural resource management.

To achieve the full potential of the ecosystem approach, it is important to train ourselves and our students to do interdisciplinary research. The currently popular terms “interdisciplinary” and “multidisciplinary” are used loosely, in my opinion, by scientists referring to ecological approaches to environmental problems. It seems to me that we approach these complex, “multi” disciplinary problems from the viewpoint of our respective disciplines (e.g. ecology, economics, sociology, hydrology, etc.) rather than at the interstices between our disciplines. It is difficult to think of examples where disciplines brought expertise to bear in an integrated manner to produce a true *inter* (between) disciplinary result for an environmental problem. We may work together or share data for a while, but rapidly retreat to the familiarity and “safety” of our own disciplines when facing extreme complexity. Thus, in my view, interdisciplinary is the goal that we all strive for in ecosystem science, but multidisciplinary is the current status.

Environmentalism

Environmentalism is the intellectual effort and activity directed at influencing and promoting political action relative to environmental issues. Often it is characterized by emotional responses to perceived changes in the environment that are thought to be detrimental to the health of organisms, particularly humans, or quality of life. Usually the goal is to protect or enhance some aspect of the environment that is judged to have value by the environmentalist. According to The Random House Dictionary (1973) an environmentalist is “any person who advocates or works to protect the air, water, animals, plants, and other natural resources from pollution or its effects.” It is interesting and informative to compare these definitions with that for ecology (Chapter I). On the one hand a focus on natural systems provides a bond between the ecologist and the environmentalist. Yet on the other, their activities and objectives are quite different. Professionally, ecologists study the environment, whereas environmentalists want to protect it. The “rules” of science dictate that ecologists must proceed in a dispassionate, formal manner without valuing the outcome of studies. Environmentalists, on the other hand, often proceed with emotion and value judgments guiding their activities. Personal values could guide the choice of question or problem to study, but once the scientist starts to pursue the answer, then

personal values cannot affect the answer. This is not to say, however, that in actual practice human beings hold these distinctions firmly in pursuit of their day-to-day activities. Individual background, training and experience provide each of us with a set of biases that we bring consciously or unconsciously to most of our endeavors. Indeed, this dichotomy leads to many conflicts such as those discussed on p. 105 ff. or those imbedded in the issues and controversies of ecotourism (see below).

Recently the Science Advisory Board of the US Environmental Protection Agency (Loehr and Lash 1990) ranked habitat alteration and destruction, species extinction, stratospheric ozone depletion and global climate change as the most serious, relatively high-risk ecological problems. In contrast, the US public considers active hazardous waste sites, abandoned hazardous waste sites, worker exposure to toxic chemicals, and destruction of the ozone layer to be the most serious environmental threats to human societies (Stevens 1991). A recent survey conducted by Ford Motor Company (HRN 1990) of leaders in business, education, media, environmental advocacy and government identified protecting ground water, improving air quality, enforcement action against polluters and reducing smog as the top environmental priorities at state and local levels, and preserving the ozone layer, improving air quality, hazardous waste disposal and reducing acid rain as the top national and international environmental issues.

The different emphasis or concern placed by these various groups in society is one measure of the complex differences between ecology and environmentalism. By and large, the public reacts to what appears to affect it directly, and when emotions are aroused government frequently responds by initiating studies and passing and enforcing laws. But are the risks real or only perceived? Are they large or small? How are they portrayed by the news media (p. 105 ff.)? The Ford Survey (HRN 1990) also found that 78% of the respondents thought that the US public would be willing to pay more for environmentally safe products, and 70% thought that the US public would accept a moderate reduction in the standard of living to protect the environment. Stevens (1991) states, "Environmentalists who have devoted themselves to causes ranked low on the priority list are unlikely to stop pushing their interests. Others resist anything that might look like an effort to practice environmental triage . . ." These examples illustrate how difficult it is for decision makers to amalgamate subjective, often emotional, environmental values with scientific data to produce realistic and ecologically sound policy decisions. It also illustrates the importance of ecological science as a provider of factual information for decision makers.

Leap-Frogging Degradation

Human use of surface freshwater resources (lakes, reservoirs, rivers, wetlands) provides one focal point where ecologists and environmentalists come into close proximity. For example, lakes are being subjected to ever-increasing human use and abuse. Pollution of surface waters is an old and pervasive problem, and because of the human health implications has been the focus of much study, legislation and mitigation. Indeed, as was described on p. 91 ff., issues relating to the availability of clean water may be among the most serious environmental problems facing human societies during the 1990's. But there is also a rather new phenomenon, not new in existence, but new in rate of occurrence. Historically, urban dwellers and those with financial means have managed to "get away", particularly during the summer months, to rather remote lakes and rivers for fishing, swimming, boating and relaxation. Frequently, this meant traveling to less crowded lake districts. In the United States, for example, vacationers often traveled to northern New England, the Adirondack Mt. region of New York State, the "Northwoods" of the midwest (Michigan, Wisconsin, Minnesota), the Sierra-Nevada Mountains, and so forth. Margins of lakes closest to urban centers became crowded with houses and cabins first, and their inhabitants subsequently not only crowded the lake's surface with boats and other recreational vehicles, but cleared vegetation, built homes, docks and other structures, installed lighting, accelerated erosion and increased noise along shorelines. The examples are numerous and with time the homes and other structures became larger and more elaborate (e.g. Diesenhouse 1991). Increased nutrients from individual sewage systems and fertilized lawns commonly produced undesirable blooms of algae, and increased use of toxic chemicals (e.g. pesticides) often contaminated water supplies. Not only was noise generated by outboard motors, chain saws and lawn mowers, but these small, fuel-burning engines made significant contributions to atmospheric pollution (volatile organic compounds, nitrogen oxides and carbon monoxide) as well (Mullins 1991). As a result of all of this and more, and particularly because of increasing numbers of humans, those with strong motivation or financial means travelled farther to find the remote, uncrowded aquatic environments that they desired. Yet in these new locations the new wave of temporary residents proceeded to repeat the same mistakes they were trying to escape. I would call this *leap-frogging degradation* and it is a common, major problem related to the use and abuse of aquatic habitats.

Conflicts are common among the diverse users of these environments, e.g. between anglers and speed boaters, between swimmers and water skiers, between residents and tourists, between bird watchers and developers, between “relaxers” and “fun-lovers”. This list is long. Klein (1985) reports that the population of common loons (*Gavia immer*), which is the classical symbol of the Northwoods environment of North America, has been decimated in many lakes because of shoreline disturbance and development; “...a necklace of summer homes...” around most lakes has led to this decline; “...no loons breed anymore in Pennsylvania, Connecticut or Rhode Island.” Most recently technology has introduced a new conflict – the so-called jet-ski or water bike (e.g. Farnsworth 1991). During July 1991 two newspaper accounts captured the essence of this conflict as related to leap-frogging degradation: from the lake district in northern Wisconsin (USA), “whether you come to the Northwoods to sail, fish, swim, water-ski or all of the above, the tranquility of the lake country stalls the busy pace of everyday life” (*Vilas County News-Review*); and from the southern part of the Adirondack Park, some 320 km north of New York City, “...the newest machines on the water go ‘rur-rur-rur-rur, in that fashion’ until you are ready to scream...” “...A New York State agency has imposed strict regulations on personal watercraft (like jet-skis).” Residents “...called the machines the scourge of summer.” (Glaberson 1991). The headline for the New York article pitted “fun and profit vs. peace and quiet...” Not only the occurrence of jet skis, but general deterioration of shoreline habitat is now appearing widely through the process of leap-frogging degradation in lake regions of northern Michigan, Wisconsin and Minnesota, the Adirondack Mt. region of New York State, the White Mt. region of New Hampshire, and elsewhere, that 15 years ago were rather remote from direct human impact of this sort. Where do humans jump to next?

Are these environmental changes ecologically important aspects of habitat deterioration in lakes and in other natural areas (e.g. Boyle 1969), or just issues that are important to environmentalists? What about erosion of shorelines from waves generated by high-speed watercraft? Although the approaches to data gathering and problem resolution are different for ecologists and environmentalists, it appears to me that many of the basic concerns and motivation for involvement are similar, if not the same. The rapidly emerging controversies related to attempts to “protect” endangered species (and their ecosystems) by raising money from tourism to support conservation (so-called ecotourism) is another good example of conflicts in

ideology and approach between ecologists and environmentalists (e.g. Hunt 1988, Dileo 1990, Peterson 1991, Tobias and Mendelsohn 1991).

Ecology, ecosystems and environmentalism often are confused by the public, by decision makers and even by scientists. As pointed out before, the term "ecology" is used widely in the news media and has come to mean many things to different people, e.g. recycling of waste products, protection of species, environmental concerns, such as clean air, conservation, or a way of life (see also Chapter I). My premise, however, is that the solution or management of environmental problems require scientific information and understanding. Indeed, environmental problems usually are identified through basic science. Acid rain or depletion of stratospheric ozone are pertinent examples. At IES, one of our important goals is to make scientific information available to managers and decision makers (e.g. Table 2), yet we believe that to be credible and effective, our touchstone must be ecological science not environmentalism.

Concluding Remarks. *I would like to finish with one of my favorite quotations, which I think epitomizes the misunderstanding that is so common between ecology as a scientific discipline and popular environmentalism. I found this quotation in an issue of the newsletter from the Australian Society of Limnology (1989). A spokesperson for the proponents of a multi-million dollar tourist and residential canal estate development stated, "Even though the development would mean the destruction of 53% of the wetland (in the Bateman's Bay area), that would be balanced by the construction of a wetlands education center to teach people of the need to protect wetlands!"*

IV EPILOGUE

Ecology is an exciting and robust science. Because of its fundamentally integrative nature, ecology has great potential for generating broad understanding about complex natural phenomena. Such ecological understanding, generated from sustained research at comprehensive ecosystem scales, can provide relevant and critical guidance to decision makers seeking solutions to environmental problems and to managers of natural resources. Also, because of the increased number of complex environmental problems throughout the world and, thus, the increased need for ecological understanding, ecology has become a popular and widely adopted concept. As a result, however, the meanings of the terms “ecology, ecosystem and environmentalism” now are frequently ambiguous and confused, and commonly abused, by both scientists and the public.

Ecosystem ecology has been particularly successful in providing management information about some of society’s most serious and vexing environmental problems such as acid rain, eutrophication, nitrate pollution, and resource management at large scales (e.g. forestry and fishery resources).

During the 1970’s the United States was the world’s leader in promoting environmental protection. For example, avante-garde legislation creating the Environmental Protection Agency (1970), the National Environmental Policy Act (1970), the Clean Air Act (1970), the Clean Water Act (1972), the Endangered Species Act (1973), the Safe Drinking Water Act (1974), and the Toxic Substances Control Act (1976) was passed with strong public support during this period. Now, this leadership role has waned; government environmental programs in the US are numerous, but expensive, often inefficient and ponderous because of their bureaucracy.

The future of the world’s human societies still depends upon natural resources. In fact, water, croplands, forests, and grasslands underpin the world’s economy. Except for fossil fuels and minerals, they supply all of the raw materials for industry. Moreover, natural, vegetated landscapes reduce erosion and filter pollutants from air and runoff water. They reduce extremes of flooding and provide food and fiber – all for “free” because these natural systems are powered by the sun (Bormann 1976). These ecosystem

services are provided by nature, but are not included in mainstream economists' cost/benefit analyses. Such benefits should be included, because these life support systems comprise our most valuable asset. When these natural life support systems are degraded or destroyed, then as a society, we must burn fossil fuels for energy to replace the functions provided by the natural ecosystem – for the construction of flood control dams and levees, for water purification systems, for air conditioning systems, and so forth. In addition, the enormous consumption of fossil fuels by humans is the basic cause of several of society's most serious and expensive environmental problems, e.g. acid rain, pollutant ozone and global warming.

C. P. Snow, in his book *In Their Wisdom* (1974), stated, "There wasn't much stamina of the soul. There was almost infinite stamina of the ego." Within that stamina of the human ego is an enormous potential and ability to solve problems. Humans are very good at solving problems. But, at the same time there is an arrogance in the human ego, characterized by "Don't worry, be happy. We'll solve it. No problem!" By following this philosophy, humans, often through willful ignorance, have generated many serious and costly environmental problems in the past. Relative to environmental degradation in today's world, a safer and more prudent philosophy to guide technological applications would be characterized as "Don't know, go slow!"

Environmental degradation is not inevitable; it is simply cheaper and easier for some in the short term. Environmental health also is not inconsistent with economic imperatives and political realities. In fact, a healthy environment is the basis for a healthy economy. Ecosystem ecology provides an important and useful approach both for assessing and for helping to restore the "health" of the biosphere.

Acknowledgements

Financial support for the Hubbard Brook Ecosystem Study (HBES) has been provided by the National Science Foundation and the Andrew W. Mellon Foundation (USA). The Hubbard Brook Experimental Forest is operated and maintained by the USDA Forest Service, Radnor, Pennsylvania. Additional financial support was provided by the Mary Flagler Cary Charitable Trust.

The section on “Environmental Issues, Scientific Communication and Ethics” is based on a lecture given at Yale University in April 1989. A chapter containing some of this material also appears in Bormann and Kellert (1991). Parts of Chapter I and the section on “Ecology, Ecosystems and Environmentalism” are based on a lecture given in Florence, Italy, in May 1991 (Likens 1992b).

Numerous colleagues have collaborated in the studies at Hubbard Brook. Drs. F. H. Bormann, N. M. Johnson, R. S. Pierce and I initiated the HBES in 1963. Intellectual leadership for the study was shared among us and I am indebted for the stimulation, support and friendship of these colleagues during the years. J. S. Eaton also was a highly valued colleague and friend during most of the study. Unfortunately, N. M. Johnson died in 1987 and J. S. Eaton in 1988. They are sorely missed. I also draw heavily on the work of numerous graduate students and postdoctoral associates.

D. C. Buso’s help with organizing and manipulating data from the Hubbard Brook Ecosystem Study is greatly appreciated. I thank T. G. Siccama for providing unpublished data on lead.

S. M. Okada’s assistance with illustrations and A. Frank’s help with library searches are gratefully acknowledged. D. C. Buso, T. J. Butler, C. T. Driscoll and S. T. A. Pickett read the entire manuscript and provided many helpful suggestions and criticisms. C. G. Jones, J. M. Miller, L. O. Hedin, D. W. Schindler and K. C. Weathers gave valuable counsel on portions of the manuscript. I am particularly grateful to J. S. Warner for assistance with the section on “Environmental Issues, Scientific Communication and Ethics”; to J. J. Cole, S. T. A. Pickett and K. C. Weathers for providing me with major input to the IES definition of ecology (Chapter I); and to my wife, Phyllis, for unfailing assistance and support including typing (word processing) numerous versions of the manuscript.

References

- Abelson, P. H. 1990. Volatile contaminants of drinking water. *Science* 247: 141
- Abelson, P. H. 1991. Desalination of brackish and marine waters. *Science* 251: 1289
- Aber, J. D., K. J. Nadelhoffer, P. Steudler and J. M. Melillo. 1989. Nitrogen saturation in northern forest ecosystems. *BioScience* 39(6): 378–386
- Aber, J. D., J. M. Melillo, K. J. Nadelhoffer, J. Pastor and R. D. Boone. 1991. Factors controlling nitrogen cycling and nitrogen saturation in northern temperate forest ecosystems. *Ecol. Appl.* 1(3): 303–315
- Ågren, G. I. and E. Bosatta. 1988. Nitrogen saturation of terrestrial ecosystems. *Environ. Pollut.* 54: 185–197
- Almer, B., W. Dickson, C. Ekström, E. Hörnström and U. Miller. 1974. Effects of acidification on Swedish lakes. *Ambio* 3: 30–36
- Amato, I. (ed.). 1991. Can PR cool the greenhouse? *Science* 252: 1784–1785
- Andren, A. W. and J. O. Nriagu. 1979. The global cycle of mercury. pp. 1–21. *In*: J. O. Nriagu (ed.). *The Biogeochemistry of Mercury in the Environment*. Elsevier/North Holland Biomedical Press, Amsterdam
- Andrewartha, H. G. 1961. *Introduction to the Study of Animal Populations*. Univ. of Chicago Press, Chicago. 281 pp.
- Andrewartha, H. G. and L. C. Birch. 1954. *The Distribution and Abundance of Animals*. Univ. of Chicago Press, Chicago. 782 pp.
- Anonymous. 1969. *Eutrophication: Causes, Consequences, and Correctives*. National Academy of Sciences, Washington, D.C. 661 pp.
- Anonymous. 1970. Dr. Vallentyne if you please: elucidate! pp. 39–40. *Canadian Research & Development*. Vol. 3, March/April, Maclean-Hunter Ltd.
- Anonymous. 1988. *Global Environmental Change. Recommendations for President-Elect George Bush*. National Academy Press, Washington, D.C. 10 pp.
- Anonymous. 1991a. *Climate Alert* 4(1): 4
- Anonymous. 1991b. *Population Update*. *Population Today* 19(10): 9
- Anonymous. 1991c. *U.S. Water News* 8(4): 12
- Anonymous. 1991d. *Water for millions: at what cost? Scenic Hudson, Poughkeepsie, New York. Bulletin No. 6*
- Anonymous. 1991e. *We're all concerned about water pollution – aren't we? Hydata* 10(5): 3
- Arimoto, R. 1989. Atmospheric deposition of chemical contaminants to the Great Lakes. *J. Great Lakes Res.* 15(2): 339–356
- Asbury, C. E. 1990. *The role of groundwater seepage in sediment chemistry and nutrient budgets in Mirror Lake, New Hampshire*. Ph.D. Thesis, Cornell University. 275 pp.
- Asbury, C. E., F. A. Vertucci, M. D. Mattson and G. E. Likens. 1989. Acidification of Adirondack lakes. *Environ. Sci. Technol.* 23(3): 362–365
- Astin, A. W., K. C. Green and W. F. Korn. 1987. *The American Freshman: Twenty-Year Trends, 1966–1985*. Cooperative Institutional Research Program, Univ. of California, Los Angeles. 225 pp.

- Australian Society of Limnology Newsletter. 1989. 27(1): 12
- Bailey, M. 1990. Ethics Schmethics?! *The Ithaca Journal*, December 28, 1990
- Baker, L. A., A. T. Herlihy, P. R. Kaufmann and J. M. Eilers. 1991. Acidic lakes and streams in the United States: the role of acidic deposition. *Science* 252: 1151–1154
- Basnet, K., G. E. Likens, F. N. Scatena and A. E. Lugo. 1992. Hurricane Hugo: damage to a tropical rain forest in Puerto Rico. *J. Tropical Ecology* 8(1): 47–50
- Berry, R. J. 1989. Ecology: where genes and geography meet. *J. Anim. Ecol.* 58: 733–759
- Bilby, R. E. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. *Ecology* 62(5): 1234–1243
- Bilby, R. E. and G. E. Likens. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. *Ecology* 61(5): 1107–1113
- Biswas, A. K. 1991. Water resources in the 21st Century. *Water International* 16: 142–144
- Bloom, N. S., C. J. Watras and J. P. Hurley. 1991. Impact of acidification on the methylmercury cycling of remote seepage lakes. *Water, Air, and Soil Pollution* 56: 477–492
- Bok, D. 1988. The President's Report, 1986–87, Harvard University. 47 pp.
- Boling, R. H., E. Goodman, J. Van Sickle, J. O. Zimmer, K. W. Cummins, R. C. Petersen and S. R. Reice. 1975. Toward a model of detritus processing in a woodland stream. *Ecology* 56: 141–151
- Booth, W. 1989. A clash of cultures at meeting on misconduct. *Science* 243: 598
- Bormann, F. H. 1976. An inseparable linkage: conservation of natural ecosystems and the conservation of fossil energy. *BioScience* 26: 754–760
- Bormann, F. H. and S. R. Kellert (eds.). 1991. *Ecology, Economics, Ethics: The Broken Circle*. Yale Univ. Press, New Haven, Connecticut. 233 pp.
- Bormann, F. H. and G. E. Likens. 1967. Nutrient cycling. *Science* 155: 424–429
- Bormann, F. H. and G. E. Likens. 1979. *Pattern and Process of a Forested Ecosystem*. Springer-Verlag, New York. 253 pp.
- Bormann, F. H. and G. E. Likens. 1985. Air and watershed management and the aquatic ecosystem. pp. 436–444. *In*: G. E. Likens (ed.). *An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment*. Springer-Verlag, New York
- Bormann, F. H. and G. E. Likens. 1987. Changing perspectives on air-pollution stress. *BioScience* 37(6): 370
- Bormann, F. H., G. E. Likens, D. W. Fisher and R. S. Pierce. 1968. Nutrient loss accelerated by clear-cutting of a forest ecosystem. *Science* 159: 882–884. Also, *In*: Proc. Symp. on Primary Productivity and Mineral Cycling in Natural Ecosystems
- Bormann, F. H., G. E. Likens and J. S. Eaton. 1969. Biotic regulation of particulate and solution losses from a forest ecosystem. *BioScience* 19(7): 600–610
- Bormann, F. H., G. E. Likens and J. M. Melillo. 1977. Nitrogen budget for an aggrading northern hardwood forest ecosystem. *Science* 196: 981–983
- Born, S. M., S. A. Smith and D. A. Stephenson. 1979. Hydrogeology of glacial-terrain lakes, with management and planning applications. *J. Hydrol.* 43: 7–43
- Boutron, C. F., U. Görlach, J-P. Candelone, M. A. Bolshov and R. J. Delmas. 1991.

- Decrease in anthropogenic lead, cadmium and zinc in Greenland snows since the late 1960s. *Nature* 353: 153–156
- Boyle, R. H. 1969. *The Hudson River*. George J. McLeod Ltd., Toronto. 304 pp.
- Braekke, F. H. 1976. Impact of acid precipitation on forest and freshwater ecosystems in Norway. SNSF Project, Oslo-Ås, Norway. 111 pp.
- Brakke, D. F., D. H. Landers and J. M. Eilers. 1988. Chemical and physical characteristics of lakes in the northeastern United States. *Environ. Sci. Technol.* 22: 153–163
- Brett, S. M. and L. M. Plunkett. 1991. Lead sources, exposures and uptake in populations at risk. *Environment* 5(2): 6–9
- Brock, T. D. 1985. *A Eutrophic Lake: Lake Mendota, Wisconsin*. Springer-Verlag, New York. 308 pp.
- Brodeur, P. 1986. Annals of chemistry in the face of doubt. *The New Yorker* (June): 70–87
- Brown, M. H. 1987. *The Toxic Cloud*. Harper and Row, New York. 307 pp.
- Brown, W. M. 1986. Hysteria about acid rain. *Fortune* 113: 125–126
- Brundtland, G. 1987. *Our Common Future*. Oxford Univ. Press, New York. 383 pp.
- Bukaveckas, P. and G. E. Likens. 1992. Long-term biogeochemical studies of Mirror Lake. (In preparation)
- Butler, T. J. and G. E. Likens. 1991. The impact of changing regional emissions on precipitation chemistry in the eastern United States. *Atmos. Environ.* 25A(2): 305–315
- Callahan, J. T. 1984. Long-term ecological research. *BioScience* 34: 363–367
- Calvert, J. (chairman). 1983. *Acid Deposition Atmospheric Processes in Eastern North America*. National Academy Press, Washington, D.C. 506 pp.
- Caraco, N., J. J. Cole and G. E. Likens. 1991. A cross-system study of phosphorus release from lake sediments. pp. 241–258. *In*: J. J. Cole, G. M. Lovett and S. E. G. Findlay (eds.). *Comparative Analyses of Ecosystems: Patterns, Mechanisms and Theories*. Springer-Verlag, New York
- Carpenter, S. R., J. F. Kitchell and J. R. Hodgson. 1985. Cascading trophic interactions and lake productivity. *BioScience* 35(10): 634–639
- Carson, Rachel. 1962. *Silent Spring*. Houghton Mifflin Co., Boston. 368 pp.
- Charles, D. F. 1985. Relationships between surface sediment diatom assemblages and lakewater characteristics in Adirondack lakes. *Ecology* 66: 994–1011
- Chen, C. W., S. A. Gherini, N. E. Peters, P. S. Murdoch, R. M. Newton and R. A. Goldstein. 1984. Hydrologic analysis of acidic and alkaline lakes. *Water Resour. Res.* 20: 1875–1882
- Christ, M., T. Siccama, D. Botkin and F. H. Bormann. 1992. Evaluating the biomass predictions of the JABOWA forest growth simulator. (In preparation)
- Christmas, J. and C. de Rooy. 1991. The decade and beyond at a glance. *Water International* 16: 127–134
- Cicerone, R. J. 1989. The hole in the ozone layer. pp. 78–89. *Science Year, World Book Annual Science Supplement*
- Cole, J. J., G. M. Lovett and S. E. G. Findlay (eds.). 1991. *Comparative Analyses of Ecosystems: Patterns, Mechanisms and Theories*. Springer-Verlag, New York
- Cosby, B. J., R. F. Wright, G. M. Hornberger and J. N. Galloway. 1985. Modeling the effects of acid deposition: estimation of long-term water quality responses in a small forested catchment. *Water Resour. Res.* 21(11): 1591–1601

- Costanza, R., F. H. Sklar and M. L. White. 1990. Modeling coastal landscape dynamics. *BioScience* 40(2): 91–107
- Cummins, K. W. 1974. Structure and function of stream ecosystems. *BioScience* 24(11): 631–641
- Cummins, K. W. 1986. Riparian influence on stream ecosystems. pp. 45–55. *In*: I. C. Campbell (ed.). *Stream protection. The Management of Rivers for Instream Uses*. Water Studies Centre, Chisholm Institute of Technology. East Caulfield, Australia
- Cummins, K. W. and M. J. Klug. 1979. Feeding ecology of stream invertebrates. *Ann. Rev. Ecol. Syst.* 10: 147–172
- Dale, V. H., L. K. Mann, R. J. Olson, D. W. Johnson and K. C. Dearstone. 1990. The long-term influence of past land use on the Walker Branch forest. *Landscape Ecology* 4(4): 211–224
- Davis, M. B. 1989. Retrospective studies. pp. 71–89. *In*: G. E. Likens (ed.). *Long-Term Studies in Ecology. Approaches and Alternatives*. Springer-Verlag, New York
- Davis, M. B. 1990. Climatic change and the survival of forest species. pp. 99–110. *In*: G. M. Woodwell (ed.). *The Earth in Transition: Patterns and Processes of Biotic Impoverishment*. Cambridge Univ. Press, Cambridge
- Davis, M. B. and C. Zabinski. 1992. Changes in geographical range resulting from greenhouse warming – effects on biodiversity in forests. *In*: R. L. Peters and T. Lovejoy (eds.). *Consequences of Greenhouse Warming to Biodiversity*. Yale Univ. Press, New Haven
- Davis, M. B., R. E. Moeller, G. E. Likens, J. Ford, J. Sherman and C. Goulden. 1985. Paleocology of Mirror Lake and its watershed. pp. 410–429. *In*: G. E. Likens (ed.). *An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment*. Springer-Verlag, New York
- Dayton, P. K., V. Currie, T. Gerrodette, B. D. Keller, R. Rosenthal and D. Van Trosca. 1984. Patch dynamics and stability of some California kelp communities. *Ecol. Monogr.* 54: 253–289
- DeAngelis, D. L., P. J. Mulholland, J. W. Elwood, A. W. Palumbo and A. D. Steinman. 1990. Biogeochemical cycling constraints on stream ecosystem recovery. *Environmental Management* 14(5): 685–697
- Derwent, R. G. and K. Nodop. 1986. Long range transport and deposition of acidic nitrogen species in northwest Europe. *Nature* 324: 356–358
- Diesenhause, S. 1991. Costs threaten “Golden Pond.” *The New York Times*, August 4, 1991; p. R12
- Dileo, M. 1990. Loved to pieces. American way. 1 September 1990. pp. 50, 52, 54, 56
- Drablos, D. and A. Tollan (eds.). 1980. Ecological impact of acid precipitation. Proc. Internat. Conf., Sandefjord, Norway. SNSF Project, Oslo-Ås, Norway. 383 pp.
- Drake, J. A., H. A. Mooney, F. di Castri, R. H. Groves, F. J. Kruger, M. Rejmánek and M. Williamson (eds.). 1989. *Biological Invasions: A Global Perspective*. Scope 37. John Wiley & Sons Ltd., London. 525 pp.
- Driscoll, C. T. and G. E. Likens. 1982. Hydrogen ion budget of an aggrading forested ecosystem. *Tellus* 34: 283–292
- Driscoll, C. T. and J. K. Otton. 1992. The speciation and cycling of trace metals. *In*:

- J. Cirny and B. Moldan. The Biogeochemistry of Small Catchments. SCOPE, J. Wiley Inc., New York. (In review)
- Driscoll, C. T., J. N. Galloway, J. F. Hornig, G. E. Likens, M. Oppenheimer, K. A. Rahn and D. W. Schindler. 1985. Is there scientific consensus on acid rain? Excerpts from six governmental reports. Ad Hoc Committee on Acid Rain: Science and Policy. Institute of Ecosystem Studies, Millbrook, New York. 13 pp.
- Driscoll, C. T., R. D. Fuller and D. M. Simone. 1988. Longitudinal variations in trace metal concentrations in a northern forested ecosystem. *J. Environ. Qual.* 17(1): 101–107
- Driscoll, C. T., G. E. Likens, L. O. Hedin, J. S. Eaton and F. H. Bormann. 1989a. Changes in the chemistry of surface waters: 25-year results at the Hubbard Brook Experimental Forest, New Hampshire. *Environ. Sci. Technol.* 23(2): 137–143
- Driscoll, C. T., G. E. Likens, L. O. Hedin and F. H. Bormann. 1989b. Reply to C. W. Chen and L. E. Gomez, "Surface water chemistry." *Environ. Sci. Technol.* 23(7): 754, 789
- Driscoll, C. T., R. M. Newton, C. P. Gubala, J. P. Baker and S. W. Christensen. 1991. Adirondack Mountains. pp. 133–202. *In*: D. F. Charles (ed.). *Acidic Deposition and Aquatic Ecosystems. Regional Case Studies.* Springer-Verlag, New York
- Driscoll, C. T., R. C. Santore and J. D. Aber. 1992. Forest and aquatic ecosystems: Modeling approach. *In*: T. Schneider (ed.). *Acidification Research: Evaluation and Policy Applications.* Elsevier Press (in press)
- Edmondson, W. T. 1969. Eutrophication in North America. pp. 124–149. *In*: *Eutrophication: Causes, Consequences and Correctives.* National Academy Sciences, Washington, D.C.
- Edmondson, W. T. 1970. Phosphorus, nitrogen and algae in Lake Washington after diversion of sewage. *Science* 169: 690–691
- Edmondson, W. T. 1972a. The present condition of Lake Washington. *Verh. Internat. Verein. Limnol.* 18: 284–291
- Edmondson, W. T. 1972b. Nutrients and phytoplankton in Lake Washington. pp. 172–195. *In*: G. E. Likens (ed.). *Nutrients and Eutrophication.* American Society Limnology and Oceanography Special Symposium 1
- Edmondson, W. T. 1990. Lessons from Washington lakes. pp. 457–463. *In*: I. G. Pop-poff, C. R. Goldman, S. L. Loeb and L. B. Leopold. *International Mountain Watershed Symposium: Subalpine Processes and Water Quality.* S. Lake Tahoe, CA. June 1988
- Edmondson, W. T. and J. T. Lehman. 1981. The effect of changes in the nutrient income on the condition of Lake Washington. *Limnol. Oceanogr.* 26: 1–29
- Edmondson, W. T. and A. H. Litt. 1982. *Daphnia* in Lake Washington. *Limnol. Oceanogr.* 26: 272–293
- Edwards, P. J., J. N. Kochenderfer and D. W. Seegrist. 1991. Effects of forest fertilization on stream water chemistry in the Appalachians. *Water Res. Bull.* 27(2): 265–274
- Ehrlich, P. R. and A. H. Ehrlich. 1990. *The Population Explosion.* Simon and Schuster, New York. 320 pp.
- Ehrlich, P. R. and E. O. Wilson. 1991. Biodiversity studies: science and policy. *Science* 253: 758–762
- Elliott, J. M. (ed.). 1990. Long-term research and the future of the aquatic environ-

- ment. *Freshwater Biology* 23(1): 1–164
- Ember, L. R., P. L. Layman, W. Lepkowski and P. S. Zuer. 1986. The changing atmosphere. Tending the global commons. *Chemical and Engineering News* 64(47): 14–64
- Falkenmark, M. 1989. The massive water scarcity now threatening Africa – why isn't it being addressed? *Ambio* 18(2): 112–118
- Farman, J. C., B. G. Gardiner and J. D. Shanklin. 1985. Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction. *Nature* 315: 207–210
- Farnsworth, C. H. 1991. Deaths on Ontario Lake fuel jet-boat dispute. *The New York Times*, 25 August 1991
- Fauci, A. 1989. Writing for my sister Denise. *The AAAS Observer* (1 September 1989), p. 4
- Federer, C. A. and D. Lash. 1978. Simulated streamflow response to possible differences in transpiration among species of hardwood trees. *Water Resour. Res.* 14: 1089–1097
- Federer, C. A., L. D. Flynn, C. W. Martin, J. W. Hornbeck and R. S. Pierce. 1990. Thirty years of hydrometeorologic data at the Hubbard Brook Experimental Forest, New Hampshire. USDA Forest Service, General Technical Report NE-141. 44 pp.
- Fenchel, T. 1987. Ecology – Potential and Limitations. *In*: O. Kinne (ed.). *Excellence in Ecology*, Vol. I. Ecology Institute, Oldendorf/Luhe, Germany. 186 pp.
- Fisher, D. C. and M. Oppenheimer. 1991. Atmospheric nitrogen deposition and the Chesapeake Bay Estuary. *Ambio* 20(3): 102–108
- Fisher, S. G. and G. E. Likens. 1973. Energy flow in Bear Brook, New Hampshire: an integrative approach to stream ecosystem metabolism. *Ecol. Monogr.* 43(2): 421–439
- Fitzgerald, W. F. and C. J. Watras. 1989. Mercury in the surficial waters of rural Wisconsin lakes. *Sci. Tot. Environ.* 87/88: 223–232
- Forman, R. T. T. and M. Godron. 1986. *Landscape Ecology*. John Wiley and Sons, New York. 620 pp.
- Franklin, J. F. 1988. Past and future of ecosystem research – contribution of dedicated experimental sites. pp. 415–424. *In*: W. T. Swank and D. A. Crossley, Jr. (eds.). *Forest Hydrology and Ecology at Coweeta*. Springer-Verlag, New York
- Franklin, J. F. 1989. Importance and justification of long-term studies in ecology. pp. 3–19. *In*: G. E. Likens (ed.). *Long-Term Studies in Ecology. Approaches and Alternatives*. Springer-Verlag, New York
- Franklin, J. F. 1992. Integrating riparian zones into the new perspectives in forestry. *In*: R. J. Naiman and J. R. Sedell (eds.). *New Perspectives for Watershed Management. Balancing Long-Term Sustainability with Cumulative Environmental Change*. Springer-Verlag, New York (in press)
- Franklin, J. F., C. S. Bledsoe and J. T. Callahan. 1990. Contributions of the long-term ecological research program. *BioScience* 40(7): 509–523
- Fuller, R. D., D. M. Simone and C. T. Driscoll. 1988. Forest clearcutting effects on trace metal concentrations: spatial patterns in soil solutions and streams. *Water, Air, and Soil Pollution* 40(1/2): 185–195
- Galloway, J. N. and G. E. Likens. 1981. Acid precipitation: the importance of nitric acid. *Atmos. Environ.* 15(6): 1081–1085

- Galloway, J. N., G. E. Likens, W. C. Keene and J. M. Miller. 1982. The composition of precipitation in remote areas of the world. *J. Geophys. Res.* 87(11): 8771–8786
- Galloway, J. N., G. E. Likens and M. E. Hawley. 1984. Acid precipitation: natural versus anthropogenic components. *Science* 226: 829–831
- Gammon, R. H., E. T. Sundquist and P. J. Fraser. 1985. History of carbon dioxide in the atmosphere. *In*: J. R. Trabalka (ed.). *Atmospheric carbon dioxide and the global carbon cycle*. U.S. Dept. of Energy DOE/ER-0239, Washington, D.C.
- Gatz, D. F., W. R. Barnard and G. J. Stensland. 1985. Proc. 78th Annual Meeting of the Air Pollut. Contr. Association, Pittsburgh, PA. Paper 85-6B.6
- Gatz, D. F., W. R. Barnard and G. J. Stensland. 1986. The role of alkaline materials in precipitation chemistry: a brief review of the issues. *Water, Air and Soil Pollution* 30: 245–251
- Gatz, D. F., F. C. Bowersox and J. Su. 1989. Lead and cadmium loadings to the Great Lakes from precipitation. *J. Great Lakes Res.* 15(2): 246–264
- Gibson, J. H. (chairman). 1986. *Acid Deposition: Long-Term Trends*. National Research Council, National Academy Press. 506 pp.
- Gill, D. E., K. A. Berven and B. A. Mock. 1983. The environmental component of evolutionary biology. pp. 1–36. *In*: C. E. King and P. S. Dawson (eds.). *Population Biology Retrospect and Prospect*. Columbia University Press, New York
- Gillis, A. M. 1990. The new forestry. *BioScience* 40(8): 558–562
- Gilmanov, T. G. 1992. A new theoretical approach to ecosystem concept as a differential of the biosphere. *In*: *First European Symposium on Terrestrial Ecosystems: Forests and Woodlands*. Florence, Italy. (In press)
- Glaberson, W. 1991. Fun and profit vs. peace and quiet at Lake George. *The New York Times*, 28 July 1991
- Glatzel, G., M. Kazda and L. Lindebner. 1986. Die Belastung von Buchenwald-ökosystemen durch Schadstoffdeposition im Nahbereich städtischer Ballungsgebiete: Untersuchungen im Wienerwald. *Düsseldorfer Geobot. Kolloq.* 3: 15–32
- Gold, A. J., W. R. DeRagon, W. M. Sullivan and J. L. Lemunyon. 1990. Nitrate-nitrogen losses to groundwater from rural and suburban land uses. *J. Soil and Water Conservation* 45(2): 305–310
- Goldfarb, B. 1989. Tap water pollutants cause a flood of concern. *USA Today*, 27 April 1989
- Goldman, C. R. 1988. Primary productivity, nutrients, and transparency during the early onset of eutrophication in ultra-oligotrophic Lake Tahoe, California-Nevada. *Limnol. Oceanogr.* 33(6, part 1): 1321–1333
- Goldman, C. R. 1990. Long-term limnological research at Lake Tahoe. pp. 464–477. *In*: I. G. Poppoff, C. R. Goldman, S. L. Loeb and L. B. Leopold (eds.). *International Mountain Watershed Symposium: Subalpine Processes and Water Quality*. S. Lake Tahoe, CA. June 1988
- Gregory, S. V., F. J. Swanson, W. A. McKee and K. W. Cummins. 1991. An ecosystem perspective of riparian zones. *BioScience* 41(8): 540–550
- Grieb, T. M., C. T. Driscoll, S. P. Gloss, C. L. Schofield, G. L. Bowie and D. B. Porcella. 1990. Factors affecting mercury accumulation in fish in the upper Michigan peninsula. *Environ. Toxicology and Chemistry* 9: 919–930
- Grover, B. and D. Howarth. 1991. Evolving international collaborative arrangements for water supply and sanitation. *Water International* 16: 145–152

- Gunn, J. M. and W. Keller. 1990. Biological recovery of an acid lake after reductions in industrial emissions of sulphur. *Nature* 345: 431–433
- Haeckel, E. 1866. *Generelle Morphologie der Organismen: Allgemeine durch die von Charles Darwin reformierte Descendenz-Theorie*. 2 vols. Reimer, Berlin
- Hairston, Sr., N. G. 1991. The literature glut: causes and consequences: reflections of a dinosaur. *Bull. Ecol. Soc. Amer.* 72(3): 171–174
- Hall, C.A.S. and J. Day (eds.). 1977. *Ecosystem Modeling in Theory and Practice*. Wiley-Interscience, New York
- Hall, R. J., G. E. Likens, S. B. Fiance and G. R. Hendrey. 1980. Experimental acidification of a stream in the Hubbard Brook Experimental Forest, New Hampshire. *Ecology* 61(4): 976–989
- Hall, R. J., C. T. Driscoll, G. E. Likens and J. M. Pratt. 1985. Physical, chemical and biological consequences of episodic aluminum additions to a stream. *Limnol. Oceanogr.* 30(1): 212–220
- Hällbacken, L. and C. O. Tamm. 1986. Changes in soil acidity from 1927 to 1982–84 in a forest area of south-west Sweden. *Scan. J. Forest Res.* 9: 219–232
- Hasler, A. D. 1947. Eutrophication of lakes by domestic drainage. *Ecology* 28: 383–395
- Hasler, A. D., O. M. Brynildson and W. T. Helm. 1951. Improving conditions for fish in brown-water bog lakes by alkalization. *J. Wildlife Management* 15: 347–352
- Havas, M., T. Hutchinson and G. E. Likens. 1984. Red herrings in acid rain research. *Environ. Sci. Technol.* 18(6): 176A–186A
- Hedin, L. O. 1990. Factors controlling sediment community respiration in woodland stream ecosystems. *Oikos* 57: 94–105
- Hedin, L. O., G. E. Likens and F. H. Bormann. 1987. Decrease in precipitation acidity resulting from decreased SO_4^{2-} concentration. *Nature* 325: 244–246
- Hedin, L. O., M. S. Mayer and G. E. Likens. 1988. The effect of deforestation on organic debris dams. *Verh. Internat. Verein. Limnol.* 23(2): 1135–1141
- Henriksen, A., L. Lien, T. S. Traaen, I. S. Sevaldrud and D. F. Brakke. 1988. Lake acidification in Norway, present and predicted chemical status. *Ambio* 17: 259–266
- Hetherington, E. D. 1985. Streamflow nitrogen loss following forest fertilization in a southern Vancouver Island watershed. *Can. J. For. Res.* 15: 34–41
- Hicks, C. 1991. Nature provides new models for production processes. National Research Council, News Report XLI(7): 14–16
- Holmes, R. T. 1990a. Ecological and evolutionary impact of bird predation on forest insects: an overview. *In*: M. C. Morrison, C. J. Ralph, J. Verner and J. R. Jehl, Jr. (eds.). *Avian Foraging: Theory, Methodology and Applications*. Studies in Avian Biology 13: 6–13
- Holmes, R. T. 1990b. Food resource availability and use in forest bird communities: a comparative view and critique. pp. 387–394. *In*: *Biogeography and Ecology of Forest Bird Communities*. SPB Academic Publications. The Hague, The Netherlands
- Holmes, R. T. 1990c. The structure of a temperate deciduous forest bird community: variability in time and space. pp. 121–139. *In*: A. Keast (ed.). *Biogeography and Ecology of Forest Bird Communities*. SPB Academic Publ., The Hague, The Netherlands

- Horn, H. S., H. H. Shugart and D. L. Urban. 1989. Simulators as models of forest dynamics. pp. 256–267. *In*: J. Roughgarden, R. M. May and S. A. Levin (eds.). *Perspectives in Ecological Theory*. Princeton Univ. Press, Princeton
- Hornbeck, J. W., R. S. Pierce and C. A. Federer. 1970. Streamflow changes after forest clearing in New England. *Water Resour. Res.* 6(4): 1124–1132
- Hornbeck, J. W., G. E. Likens and J. S. Eaton. 1976. Seasonal patterns in acidity of precipitation and the implications for forest-stream ecosystems. pp. 597–609. *In*: L. S. Dochinger and T. A. Seliga (eds.). *Proc. The First Internat. Symp. on Acid Precipitation and the Forest Ecosystem*. USDA Forest Service General Tech. Report NE-23; also *Water, Air, and Soil Pollution* 7: 355–365 [1977]
- Hrbáček, J., M. Dvorkova, V. Korínek and L. Procházková. 1961. Demonstration of the effect of the fish stock on the species composition of zooplankton and the intensity of metabolism of the whole plankton association. *Verh. Internat. Verein. Limnol.* 14: 192–195
- HRN. 1990. 1989 Environmental issues and priorities survey. Executive Summary. HRN, Philadelphia, PA. 23 pp.
- Hughes, C. 1991. Mexico is sucking one of its largest lakes dry. *The Ithaca Journal*, 20 August 1991
- Hultberg, H. and G. E. Likens. 1992. Sulphur deposition to forested ecosystems in northern Europe and North America – Large-scale variations and long-term dynamics. *In*: Fifth International Conf. on Precipitation Scavenging and Atmosphere-Surface Exchange Processes. Richland, Washington. (In press)
- Hunt, C. 1988. Put on your hiking boots and poncho. This is central Africa, and you've got a date with a gorilla. *Travel and Leisure* 18(10): 104–113
- Hurlbert, S. H. 1984. Pseudoreplication and the design of ecological field experiments. *Ecol. Monogr.* 54(2): 187–211
- Hursh, C. R., M. D. Hoover and P. W. Fletcher. 1942. Studies in the balanced water economy of experimental drainage areas. *Trans. Amer. Geophys. Union*, Part 2: 509–517
- Huston, M., D. DeAngelis and W. Post. 1988. New computer models unify ecological theory. *BioScience* 38(10): 682–691
- Hutchinson, G. E. 1950. Survey of contemporary knowledge of biogeochemistry. III. The biogeochemistry of vertebrate excretion. *Bull. Amer. Mus. Nat. History* 96, 554 pp.
- Hutchinson, G. E. 1957. *A Treatise on Limnology, Vol. I. Geography, Physics and Chemistry*. John Wiley and Sons, New York. 1015 pp.
- Hutchinson, G. E. 1967. *A Treatise on Limnology, Vol. II. Introduction to Lake Biology and the Limnoplankton*. John Wiley and Sons, New York. 1115 pp.
- Hutchinson, G. E. 1973. Eutrophication. The scientific background of a contemporary practical problem. *Amer. Sci.* 61: 269–279
- Hutchinson, G. E. 1975. *A Treatise on Limnology, Vol. III. Limnological Botany*. John Wiley and Sons, New York. 660 pp.
- International Lake Erie and Lake Ontario – St. Lawrence River Water Pollution Boards. 1969. Pollution of Lake Erie, Lake Ontario and the international section of the St. Lawrence River. Vol. I. – Summary. pp. 1–151
- Jacobson, J. L. 1989. Swept away. *World Watch* 2(1): 20–26
- Janovy, Jr., J. 1985. *On Becoming a Biologist*. Harper and Row, New York. 160 pp.

- Jaroff, L. 1991. Crisis in the labs. *Time* 138(8): 44–51
- Johnson, D. W. and R. I. Van Hook (eds.). 1989. *Biogeochemical Cycling in Walker Branch Watershed: A Synthesis of Research Results*. Springer-Verlag, New York. 401 pp.
- Johnson, D. W., R. J. Olson, L. K. Mann and D. E. Todd. 1990. Long-term changes in biomass and nutrient cycling in forests of Walker Branch Watershed, Tennessee. pp. 122–136. *In*: S. P. Gessel, D. S. LaCate, G. F. Weetman and R. F. Powers (eds.). Vancouver: Forestry Publications. Univ. of British Columbia
- Johnson, N. M., G. E. Likens, F. H. Bormann, D. W. Fisher and R. S. Pierce. 1969. A working model for the variation in stream water chemistry at the Hubbard Brook Experimental Forest, New Hampshire. *Water Resour. Res.* 5(6): 1353–1363
- Johnson, N. M., C. T. Driscoll, J. S. Eaton, G. E. Likens and W. H. McDowell. 1981. "Acid rain," dissolved aluminum and chemical weathering at the Hubbard Brook Experimental Forest, New Hampshire. *Geochim. Cosmochim. Acta* 45(9): 1421–1437
- Johnson, W. E. and A. D. Hasler. 1954. Rainbow trout population in dystrophic lakes. *J. Wildlife Management* 18: 113–134
- Jónasson, P. M. (ed.). 1979. *Ecology of Eutrophic, Subarctic Lake Mývatn and the River Laxá*. Icelandic Literature Soc., Copenhagen. 308 pp.
- Jones, C. G. and M. Shachak. 1990. Fertilization of the desert soil by rock-eating snails. *Nature* 346: 839–841
- Juday, C. and C. L. Schloemer. 1938. Effect of fertilizers on plankton production and on fish growth in a Wisconsin lake. *Progressive Fish Culturist* 40: 24–27
- Kämäri, J., M. Forsius, P. Kortelainen, J. Mammio and M. Verta. 1991. Finnish lake survey: present status of acidification. *Ambio* 20(1): 23–27
- Keeling, C. E. 1960. The concentration and isotopic abundances of carbon dioxide in the atmosphere. *Tellus* 12: 200–203
- Keeling, C. E. 1973. Industrial production of carbon dioxide from fossil fuels and limestone. *Tellus* 28: 174–198
- Kelly, T. J., J. M. Czuczwa, P. R. Sticksel and G. M. Sverdrup. 1991. Atmospheric and tributary inputs of toxic substances to Lake Erie. *J. Great Lakes Res.* 17(4): 504–516
- Kerr, R. A. 1991. The lessons of Dr. Browning. *Science* 253: 622–623
- Kinne, O. 1980. Diseases of marine animals: general aspects. pp. 13–73. *In*: O. Kinne (ed.). *Diseases of Marine Animals*. John Wiley and Sons, Chichester
- Kinne, O. 1988. The scientific process – its links, functions and problems. *Naturwissenschaften* 75: 275–279
- Klein, T. 1985. *Loon Magic*. Paper Birch Press, Inc., Ashland, Wisconsin. 145 pp.
- Kohl, D. H., G. B. Shearer and B. Commoner. 1971. Fertilizer nitrogen: contribution to nitrate in surface water in a corn belt watershed. *Science* 174: 1331–1334
- Kohout, E. J., D. J. Miller, L. A. Nieves, D. S. Rothman, C. L. Saricks, F. Stodolsky and D. A. Hanson. 1990. Current emission trends for nitrogen oxides, sulfur dioxide, and volatile organic compounds by month and state: methodology and results. Report for National Acid Precipitation Assessment Program, U.S. Department of Energy. ANL/EAIS/TM-25
- Kramer, J. R., A. W. Andren, R. A. Smith, A. H. Johnson, R. B. Alexander and G. Oehlert. 1986. Streams and lakes. pp. 231–299. *In*: National Research Council,

- Committee on Monitoring and Assessment of Trends in Acid Deposition. Acid Deposition: Long-Term Trends. National Academy Press, Washington, D.C.
- Krebs, C. J. 1972. Ecology: The experimental analysis of distribution and abundance. Harper and Row, New York. 694 pp.
- Kretser, W. A., J. Gallagher and J. Nicolette. 1989. Adirondack Lakes Survey 1984–1987: An Evaluation of Fish Communities and Water Chemistry. Adirondack Lakes Survey Corporation. Ray Brook, New York
- Kulp, L. 1987. Interim assessment. The causes and effects of acidic deposition. Volume I. Executive Summary. National Acid Precipitation Assessment Program. Washington, D.C.
- Landers, D. H., W. S. Overton, R. A. Linthurst and D. F. Brakke. 1988. Eastern lake survey: regional estimates of lake chemistry. Environ. Sci. Technol. 22: 128–135
- Lawes Agricultural Trust. 1984. Rothamsted: The classical experiments. Rothamsted Agric. Exp. Sta., Harpenden, U.K.
- Lawrence, G. B. and C. T. Driscoll. 1990. Longitudinal patterns of concentration-discharge relationships in stream water draining the Hubbard Brook Experimental Forest, New Hampshire. J. Hydrology 116: 147–165
- Lawrence, G. B., R. D. Fuller and C. T. Driscoll. 1986. Spatial relationships of aluminum chemistry in the streams of the Hubbard Brook Experimental Forest, New Hampshire. Biogeochemistry 2: 115–135
- Lawrence, G. B., C. T. Driscoll and R. D. Fuller. 1988. Hydrologic control of aluminum chemistry in an acidic headwater stream. Water Resour. Res. 24: 659–669
- Leff, L. G. and J. V. McArthur. 1990. Effect of nutrient content on leaf decomposition in a coastal plain stream: a comparison of green and senescent leaves. J. Fresh. Ecol. 5(3): 269–277
- Legge, R. F. and D. Dingeldein. 1970. We hung phosphates without a fair trial. pp. 19–27. Canadian Research and Development March/April. Vol. 3, Maclean-Hunter Ltd.
- Leopold, A. 1939. A biotic view of land. J. Forestry 37: 727–730
- Leopold, A. 1940. Song of the Gavilan. J. Wildl. Management 4(3): 329–332
- Levy, H. and W. J. Moxim. 1987. Fate of U.S. and Canadian combustion nitrogen emissions. Nature 328: 414–416
- Likens, G. E. (ed.). 1972. Nutrients and Eutrophication. Proc. American Society of Limnology and Oceanography Special Symposia, Vol. 1. Lawrence, Kansas
- Likens, G. E. 1975. Nutrient flux and cycling in freshwater ecosystems. pp. 314–348. In: F. G. Howell, J. B. Gentry and M. H. Smith (eds.). Mineral Cycling in Southeastern Ecosystems. ERDA Symp. Series CONF-740513. Augusta, Georgia
- Likens, G. E. 1983. A priority for ecological research. Bull. Ecol. Soc. Amer. 64(4): 234–243
- Likens, G. E. 1984. Beyond the shoreline: a watershed-ecosystem approach. Verh. Internat. Verh. Limnol. 22: 1–22
- Likens, G. E. 1985a. The aquatic ecosystem and air-land-water interactions. pp. 430–444. In: G. E. Likens (ed.). An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment. Springer-Verlag, New York
- Likens, G. E. (ed.). 1985b. An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment. Springer-Verlag, New York. 516 pp.
- Likens, G. E. 1985c. An experimental approach for the study of ecosystems. J. Ecol.

- 73: 381–396
- Likens, G. E. (ed.). 1989a. Long-Term Studies in Ecology. Approaches and Alternatives. Springer-Verlag, New York. 214 pp.
- Likens, G. E. 1989b. Some aspects of air pollution effects on terrestrial ecosystems and prospects for the future. *Ambio* 18(3): 172–178
- Likens, G. E. 1991. Human-accelerated environmental change. *BioScience* 41(3): 130
- Likens, G. E. 1992a. Environmental problems in the 1990's: an ecological perspective. *In: Environmental Problems: Global and Regional Concerns*. Vermont Academy of Arts and Sciences, Burlington, VT (in press)
- Likens, G. E. 1992b. Some applications of the ecosystem approach to environmental problems and resource management. *In: First European Symposium on Terrestrial Ecosystems: Forests and Woodlands*. Florence, Italy. May 1991. (In press)
- Likens, G. E. and R. E. Bilby. 1982. Development, maintenance and role of organic-debris dams in New England streams. pp. 122–128. *In: F. J. Swanson, R. J. Janda, T. Dunne and D. N. Swanston (eds.)*. Sediment Budgets and Routing in Forested Drainage Basins. USDA Forest Service General Technical Report PNW-141
- Likens, G. E. and F. H. Bormann. 1972. Nutrient cycling in ecosystems. pp. 25–67. *In: J. Wiens (ed.)*. Ecosystem Structure and Function. Oregon State Univ. Press, Corvallis
- Likens, G. E. and F. H. Bormann. 1974. Acid rain: a serious regional environmental problem. *Science* 184: 1176–1179
- Likens, G. E. and F. H. Bormann. 1985. An Ecosystem Approach. pp. 1–8. *In: G. E. Likens (ed.)*. An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment. Springer-Verlag, New York
- Likens, G. E. and G. R. Hendrey. 1977. Acid precipitation (letter response). *Chemical and Engineering News* 55(25): 60–61
- Likens, G. E., F. H. Bormann and N. M. Johnson. 1969. Nitrification: importance to nutrient losses from a cutover forested ecosystem. *Science* 163: 1205–1206
- Likens, G. E., F. H. Bormann, N.M. Johnson, D. W. Fisher and R. S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. *Ecol. Monogr.* 40(1): 23–47
- Likens, G. E., F. H. Bormann and N. M. Johnson. 1972. Acid rain. *Environment* 14(2): 33–40
- Likens, G. E., F. H. Bormann, R. S. Pierce, J. S. Eaton and N. M. Johnson. 1977. Biogeochemistry of a Forested Ecosystem. Springer-Verlag, New York. 146 pp.
- Likens, G. E., R. F. Wright, J. N. Galloway and T. J. Butler. 1979. Acid rain. *Sci. Amer.* 241(4): 43–51
- Likens, G. E., F. H. Bormann, R. S. Pierce, J. S. Eaton and R. E. Munn. 1984. Long-term trends in precipitation chemistry at Hubbard Brook, New Hampshire. *Atmos. Environ.* 18(12): 2641–2647
- Likens, G. E., F. H. Bormann, R. S. Pierce and J. S. Eaton. 1985a. The Hubbard Brook Valley. pp. 9–39. *In: G. E. Likens (ed.)*. An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment. Springer-Verlag, New York
- Likens, G. E., J. S. Eaton, N. M. Johnson and R. S. Pierce. 1985b. Flux and balance of water and chemicals. pp. 135–155. *In: G. E. Likens (ed.)*. An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment. Springer-Verlag,

New York

- Likens, G. E., W. C. Keene, J. M. Miller and J. N. Galloway. 1987. Chemistry of precipitation from a remote, terrestrial site in Australia. *J. Geophys. Res.* 92(D11): 13 299–13 314
- Likens, G. E., L. O. Hedin and T. J. Butler. 1990a. Some long-term precipitation chemistry patterns at the Hubbard Brook Experimental Forest: extremes and averages. *Verh. Internat. Verein. Limnol.* 24(1): 128–135
- Likens, G. E., F. H. Bormann, L. O. Hedin, C. T. Driscoll and J. S. Eaton. 1990b. Dry deposition of sulfur: A 13-yr record for the Hubbard Brook Forest Ecosystem. *Tellus* 42B: 319–329
- Lindberg, S., P. M. Stokes and E. Goldberg. 1987. Group Report: Mercury. Chapter 2. pp. 17–33. *In*: T. C. Hutchinson and K. M. Meema (eds.). *Lead, Mercury, Cadmium and Arsenic in the Environment*. SCOPE, John Wiley and Sons, Chichester
- Lisher, M. 1991. Fertilizer overdoses harm fields, water. *The Milwaukee Journal*, 6 September 1991, p. B11
- Little, R. 1989. Environmental concerns grow. *USA Today*, 17 May 1991
- Loehr, R. and J. Lash (chairs). 1990. Reducing risk: setting priorities and strategies for environmental protection. SAB-EC-90-021 U.S. Environmental Protection Agency, Washington, D.C. 26 pp.
- Löfuendahl, R. 1990. Changes in the flux of some major dissolved components in Swedish rivers during the present century. *Ambio* 19(4): 210–219
- Loucks, O. L. 1992. Science or policy? NAPAP, 1980–1990. *Forum for Applied Research and Public Policy* 7(1): (in press)
- Lovett, G. M. and J. D. Kinsman. 1990. Atmospheric pollutant deposition to high-elevation ecosystems. *Atmos. Environ.* 24A(11): 2767–2786
- Lovett, G. M., W. A. Reiners and R. K. Olson. 1982. Cloud droplet deposition in sub-alpine balsam fir forests: hydrological and chemical inputs. *Science* 218: 1303–1304
- Lowrance, R. R., R. L. Todd and L. E. Asmussen. 1984. Nutrient cycling in an agricultural watershed: I. Phreatic movement. *J. Environ. Qual.* 13(1): 22–32
- Luoma, J. R. 1990. New logging approach tries to mimic nature. *The New York Times*, 12 June 1990; p. C1, C13
- Luxmoore, R. J., P. M. Jardine, G. V. Wilson, J. R. Jones and L. W. Zelazny. 1990. Physical and chemical controls of preferred path flow through a forested hillslope. *Geoderma* 46: 139–154
- Magnuson, J. J. 1990. Long-term ecological research and the invisible present. *BioScience* 40(7): 495–501
- Makarewicz, J. C. and P. Bertram. 1991. Evidence for the restoration of the Lake Erie ecosystem. *BioScience* 41(4): 216–223
- Marshall, E. 1989. NSF peer review under fire from Nader group. *Science* 245: 250
- Mason, J. W., G. D. Wegner, G. I. Quinn and E. L. Lange. 1990. Nutrient loss via groundwater discharge from small watersheds in southwestern and south central Wisconsin. *J. Soil and Water Conservation* 45(2): 327–331
- McDonnell, J. J. 1990. A rationale for old water discharge through macropores in a steep, humid catchment. *Water Resour. Res.* 26: 2821–2832
- McDonnell, M. J. and S.T.A. Pickett. 1990. Ecosystem structure and function along urban-rural gradients: an unexploited opportunity for ecology. *Ecology* 71(4):

- 1232–1237
- McDowell, W. H. 1982. Mechanisms controlling the organic chemistry of Bear Brook, New Hampshire. Ph.D. Thesis, Cornell University. 152 pp.
- McDowell, W. H. 1985. Kinetics and mechanisms of dissolved organic carbon retention in a headwater stream. *Biogeochemistry* 1: 329–352
- McDowell, W. H. and G. E. Likens. 1988. Origin, composition, and flux of dissolved organic carbon in the Hubbard Brook Valley. *Ecol. Monogr.* 58(3): 177–195
- McDowell, W. H. and T. Wood. 1984. Podzolization: soil processes control dissolved organic carbon concentrations in stream water. *Soil Sci.* 137(1): 23–32
- McIntosh, R. P. 1985. *The Background of Ecology Concept and Theory*. Cambridge Univ. Press, New York. 383 pp
- McIntosh, R. P. 1990. Ecology as metaphor. Miami University Symposium, *The Role of Landscape Ecology in Public Policy-Making and Land-Use Management*. March 1990. Oxford, Ohio
- Medawar, P. B. 1979. *Advice to a young scientist*. Harper and Row, London. 109 pp.
- Meyer, J. L. 1979. The role of sediments and bryophytes in phosphorus dynamics in a headwater stream. *Limnol. Oceanogr.* 24(2): 365–375
- Meyer, J. L. and G. E. Likens. 1979. Transport and transformation of phosphorus in a forest stream ecosystem. *Ecology* 60(6): 1255–1269
- Meyer, J. L., G. E. Likens and J. Sloane. 1981. Phosphorus, nitrogen, and organic carbon flux in a headwater stream. *Arch. Hydrobiol.* 91(1): 28–44
- Molina, M. J. and F. S. Rowland. 1974. Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone. *Nature* 249: 810–812
- Moody, D. W. 1990. Groundwater contamination in the United States. *J. Soil Water Conservation* 45(2): 170–179
- Mulholland, P. J., G. V. Wilson and P. M. Jardin. 1990. Hydrogeochemical response of a forested watershed to storms: effects of preferential flow along shallow and deep pathways. *Water Resources Res.* 26(12): 3021–3036
- Mullins, M. E. 1991. Off-road engine pollution. *USA Today*, 30 October 1991
- National Academy of Sciences, National Research Council. 1992. *Ozone: Sources, Formation and Measurement of Urban and Regional Air Pollution*. National Academy Press, Washington, D.C.
- Nilsson, J. and P. Grennfelt (eds.). 1988. *Critical Loads for Sulphur and Nitrogen*. International Workshop, UN-ECE and Nordin Council Ministers, Stockholm, Sweden. Miljörapport 1988: 15. 418 pp.
- Norton, S. A. (chairman). 1984. *Acid Deposition: Processes of Lake Acidification*. National Research Council, National Academy Press, Washington, D.C.
- Odén, S. 1968. The acidification of air and precipitation and its consequences on the natural environment. Swedish National Science Research Council, Ecology Committee, Bulletin 1. 68 pp.
- Odum, E. P. 1959. *Fundamentals of Ecology*, 2nd edition. W. B. Saunders Co., Philadelphia. 546 pp.
- Odum, E. P. 1971. *Fundamentals of Ecology*, 3rd edition. W. B. Saunders Co., Philadelphia. 574 pp.
- Office of Technology Assessment. 1984. *Acid rain and transported air pollutants: Implications for public policy*. Report OTA-0-204. Office of Technology Assessment, U.S. Congress, Washington, D.C. 323 pp.

- Orghidan, T. 1959. Ein neuer Lebensraum des unterirdischen Wassers: Der hyporheische Biotop. *Arch. für Hydrobiologie* 55: 392–414
- Pacyna, J. M. 1987. Atmospheric emissions of arsenic, cadmium, lead and mercury from high temperature processes in power generation and industry. Chapter 7. pp. 69–87. *In*: T. C. Hutchinson and K. M. Meema (eds.). *Lead, Mercury, Cadmium and Arsenic in the Environment*. SCOPE, John Wiley and Sons, Chichester
- Paine, R. T. 1966. Food web complexity and species diversity. *The Amer. Natur.* 100(910): 65–75
- Parker, S. 1989. Water supply runs low. *USA Today*, 24 March 1989
- Peierls, B. L., N. F. Caraco, M. L. Pace and J. J. Cole. 1991. Human influence on river nitrogen. *Nature* 350: 386–387
- Persson, G., H. Olsson, T. Wiederholm and E. Willen. 1989. Lake Vättern, Sweden: a 20-year perspective. *Ambio* 18: 208–215
- Peters, N. E. and C. T. Driscoll. 1987. Hydrogeologic controls of surface water chemistry in the Adirondack region of New York State. *Biogeochemistry* 3: 163–180
- Peters, R. H., J. J. Armesto, B. Boeken, J. J. Cole, C. T. Driscoll, C. M. Duarte, T. M. Frost, J. P. Grime, J. Kolasa, E. Prepas and W. G. Sprules. 1991. On the relevance of comparative ecology to the larger field of ecology. pp. 46–64. *In*: J. J. Cole, G. M. Lovett and S.E.G. Findlay (eds.). *Comparative Analyses of Ecosystems: Patterns, Mechanisms, and Theories*. Springer-Verlag, New York
- Peterson, R. T. 1991. Ecotourism – the new buzzword. *Bird Watcher's Digest* 13(6): 12–22
- Pickett, S. T. A. 1989. Space-for-Time substitution as an alternative to long-term studies. pp. 110–135. *In*: G. E. Likens (ed.). *Long-Term Studies in Ecology. Approaches and Alternatives*. Springer-Verlag, New York
- Pickett, S. T. A., V. T. Parker and P. L. Fiedler. 1992. The new paradigm in ecology: Implications for conservation biology above the species level. *In*: P. L. Fiedler and S. K. Jain (eds.). *Conservation Biology: The Theory and Practice of Nature Conservation, Preservation, and Management*. Chapman and Hall, New York (in press)
- Pierce, R. S., J. W. Hornbeck, G. E. Likens and F. H. Bormann. 1970. Effect of elimination of vegetation on stream water quantity and quality. pp. 311–328. *In*: *Internat. Symp. on Results of Research on Representative and Experimental Basins*. Internat. Assoc. Sci. Hydrol., Wellington, New Zealand
- Postel, S. 1989. Water for agriculture: facing the limits. *Worldwatch Paper* 93. Worldwatch Institute, Washington, D.C. 54 pp.
- Powledge, F. 1984. The magnificent liquid of life. *National Wildlife* 22(2): 7–9
- Rahn, K. A., R. D. Borys, G. E. Shaw, L. Schutz and R. Jaenicke. 1979. Long-range impact of desert aerosol on atmospheric chemistry: two examples. pp. 243–266. *In*: C. Morales (ed.). *Saharan Dust Mobilization, Transport, Deposition*. SCOPE 14. John Wiley and Sons, Chichester
- The Random House Dictionary of the English Language. 1973. Random House, New York
- Redfield, A. C. 1958. The biological control of chemical factors in the environment. *Amer. Sci.* 46: 206–226
- Richardson, W. B. 1990. A comparison of detritus processing between permanent and intermittent headwater streams. *J. Fresh. Ecol.* 5(3): 341–357

- Risser, P. G. (ed.). 1991. Long-Term Ecological Research: An International Perspective. John Wiley and Sons, Chichester. 294 pp.
- Roberts, L. 1991. Learning from the acid rain program. *Science* 251: 1302–1305
- Roskoski, J. P. 1977. Nitrogen fixation in northern hardwood forests. Ph.D. Thesis, Yale University. 112 pp.
- Roughgarden, J., R. M. May and S. A. Levin (eds.). 1989. Perspectives in Ecological Theory. Princeton Univ. Press, Princeton
- Rounick, J. S. and M. J. Winterbourne. 1983. Leaf processing in two contrasting beech forest streams: effects of physical and biotic factors on litter breakdown. *Arch. Hydrobiol.* 96: 448–474
- Rowland, F. S. 1989. Chlorofluorocarbons and the depletion of stratospheric ozone. *Amer. Sci.* 77: 36–45
- Rowland, F. S. and M. J. Molina. 1975. Chlorofluoromethanes in the environment. *Rev. Geophys. Space Phys.* 13: 1–35
- Ruttner, F. 1963. Fundamentals of Limnology. (Translated by D. Frey and F. E. J. Frey). Univ. of Toronto Press. 295 pp.
- Schindler, D. W. 1973. Experimental approaches to limnology – an overview. *J. Fish. Res. Bd. Canada* 30: 1409–1413
- Schindler, D. W. 1974. Experimental studies of eutrophication and lake recovery: some implications for lake management. *Science* 184: 897–899
- Schindler, D. W. 1977. Evolution of phosphorus limitation in lakes. *Science* 195: 260–262
- Schindler, D. W. 1980. Evolution of the Experimental Lakes Project. *Canadian J. Fish. Aquat. Sci.* 37: 313–319
- Schindler, D. W. (chairman). 1981. Atmosphere-Biosphere Interactions: Toward a Better Understanding of the Ecological Consequences of Fossil Fuel Combustion. National Research Council, National Academy Press, Washington, D.C.
- Schindler, D. W. 1988a. Effects of acid rain on freshwater ecosystems. *Science* 239: 149–157
- Schindler, D. W. 1988b. Experimental studies of chemical stressors on whole lake ecosystems. *Verh. Internat. Verein. Limnol.* 23: 11–41
- Schindler, D. W., G. J. Brunskill, S. Emerson, W. S. Broecker and T. H. Peng. 1972. Atmospheric carbon dioxide: Its role in maintaining phytoplankton standing crops. *Science* 177: 1192–1194
- Schindler, D. W., K. H. Mills, D. F. Malley, D. D. Findlay, J. A. Shearer, I. J. Davies, M. A. Turner, G. A. Linsey and D. R. Cruikshank. 1985. Long-term ecosystem stress: the effects of years of experimental acidification on a small lake. *Science* 228: 1395–1401
- Schneider, K. 1991. Ancient hazards of mercury re-emerge. *The New York Times*, 26 August 1991, pp. A1, B5
- Schofield, C. L. 1976. Acid precipitation: effects on fish. *Ambio* 5: 228–230
- Schofield, C. L. 1980. Processes limiting fish populations in acidified lakes. pp. 345–355. *In*: D. S. Shriner, C. R. Richmond and S. E. Lindberg (eds.). Atmospheric Sulfur Deposition: Environmental Impact and Health Effects. Ann Arbor Science Publishers Inc., Ann Arbor, MI
- Schofield, C. L. 1982. Historical fisheries changes in the United States related to decreases in surface water pH. pp. 57–67. *In*: R. E. Johnson (ed.). Acid Rain/

- Fisheries. American Fisheries Society, Bethesda, Maryland
- Schofield, C. L. and J. R. Trojnar. 1980. Aluminum toxicity to fish in acidified waters. pp. 347–366. *In*: T. Y. Toribara, M. W. Miller and P. E. Morrow (eds.). *Polluted Rain*. Plenum Press, New York
- Scott, J. T., T. G. Siccama, A. H. Johnson and A. R. Breisch. 1984. Decline of red spruce in the Adirondacks, New York U.S.A. *Bull. Torrey Botanical Club* 111(4): 438–444
- Sedell, J. R., F. J. Triska, J. S. Hall, N. H. Anderson and J. H. Lyford. 1973. Sources and fates of organic inputs in coniferous forest streams. Contribution 66, pp. 1–23. *Coniferous Forest Biome. Internat. Biol. Prog.*, Oregon St. University, Corvallis (Oregon)
- Shachak, M., C. G. Jones and Y. Granot. 1987. Herbivory in rocks and the weathering of a desert. *Science* 236: 1098–1099
- Shachak, M., C. G. Jones and S. Brand. 1992. The role of animals in arid ecosystems: snails and isopods as controllers of soil formation, erosion and desalinization. *Catena* (in press)
- Shea, C. P. 1988. The chlorofluorocarbon dispute why Du Pont gave up \$600 million. *The New York Times*, 10 April 1988
- Shugart, H. H. 1989. The role of ecological models in long-term ecological studies. pp. 90–109. *In*: G. E. Likens (ed.). *Long-Term Studies in Ecology. Approaches and Alternatives*. Springer-Verlag, New York
- Siccama, T. G. and W. H. Smith. 1978. Lead accumulation in a northern hardwood forest. *Environ. Sci. Technol.* 12: 593–594
- Siccama, T. G., W. H. Smith and D. L. Mader. 1980. Changes in lead, zinc, copper, dry weight and organic matter content of the forest floor of white pine stands in central Massachusetts over 16 years. *Environ. Sci. Technol.* 14: 54–56
- Singer, F. J., W. T. Swank and E. E. C. Clebsch. 1984. Effects of wild pig rooting in a deciduous forest. *J. Wildlife Management* 48(2): 464–473
- Sloane, J. 1979. Nitrogen flux in small mountain streams in New Hampshire. M.S. Thesis, Cornell University. 131 pp.
- Smith, W. H. and T. G. Siccama. 1981. The Hubbard Brook Ecosystem Study: biogeochemistry of lead in the northern hardwood forest. *J. Environ. Qual.* 10: 323–333
- Smith, R. A. 1872. *Air and Rain. The Beginnings of Chemical Climatology*. Longmans, Green and Co., London. 600 pp.
- Sprugel, D. G. and F. H. Bormann. 1981. Natural disturbance and the steady state in high altitude balsam fir forests. *Science* 211: 390–393
- Stanford, J. A. and J. V. Ward. 1988. The hyporheic habitat of river ecosystems. *Nature* 335: 64–66
- Stensland, G. J. and R. G. Semonin. 1982. Another interpretation of the pH trend in the United States. *Bull. Amer. Meteor. Soc.* 63: 1277–1284
- Stevens, W. K. 1991. What really threatens the environment? *The New York Times*, 29 January 1991. p. C4
- Strayer, D., J. S. Glitzenstein, C. G. Jones, J. Kolasa, G. E. Likens, M. J. McDonnell, G. G. Parker and S.T.A. Pickett. 1986. Long-term ecological studies: An illustrated account of their design, operation, and importance to ecology. Occasional Publication of the Institute of Ecosystem Studies, No. 2. Millbrook, NY.

- 38 pp.
- Streets, D. G. and T. D. Veselka. 1987. Future emissions. pp. 3-1 to 3-33. *In*: Interim Assessment of the National Acid Precipitation Assessment Program, Washington, D.C.
- Stresky, S. J. 1991. Morphology and flow characteristics of pipes in a forested New England slope. M.S. Thesis, University of New Hampshire, Durham
- Stross, R. G. and A. D. Hasler. 1960. Some lime-induced changes in lake metabolism. *Limnol. Oceanogr.* 5: 265-272
- Swank, W. T. and D. A. Crossley, Jr. 1988. *Forest Hydrology and Ecology at Coweeta*. Springer-Verlag, New York. 469 pp.
- Swank, W. T., J. B. Waide, D. A. Crossley, Jr. and R. L. Todd. 1981. Insect defoliation enhances nitrate export from forest ecosystems. *Oecologia* 51: 297-299
- Tamm, C. O. 1991. *Nitrogen in Terrestrial Ecosystems*. Springer-Verlag, Berlin. 115 pp.
- Tamm, C. O. and Hällbacken. 1986. Changes in soil pH over a 50-year period under different forest canopies in SW Sweden. *Water, Air, and Soil Pollution* 31: 337-341
- Tamm, C. O. and L. Hällbacken. 1988. Changes in soil acidity in two forest areas with different acid deposition: 1920's to 1980's. *Ambio* 17(1): 56-61
- Tamm, C. O. and T. Troedsson. 1955. An example of the amounts of plant nutrients supplied to the ground in road dust. *Oikos* 6: 61-70
- Tansley, A. G. 1935. The use and abuse of vegetational concepts and terms. *Ecology* 16: 284-307
- Tilman, D. 1989. Ecological experimentation: strengths and conceptual problems. pp. 136-157. *In*: G. E. Likens (ed.). *Long-Term Studies in Ecology. Approaches and Alternatives*. Springer-Verlag, New York
- Tobias, D. and R. Mendelsohn. 1991. Valuing ecotourism in a tropical rain-forest reserve. *Ambio* 20: 91-93
- Turner, M. G. 1990. Spatial and temporal analysis of landscape patterns. *Landscape Ecology* 4(1): 21-30
- Turner, M. G. and R. Gardner (eds.). 1991. *Quantitative Methods in Landscape Ecology*. Springer-Verlag, New York. 536 pp.
- Ulrich, B., R. Mayer and P. K. Khanna. 1979. Deposition von Luftverunreinigungen und ihre Auswirkungen in Waldökosystemen im Solling. *Schriften aus der Forstlichen Fakultät der Universität Göttingen und der Niedersächsischen Forstlichen Versuchsanstalt*. J. D. Sauerländer's Verlag, Frankfurt. 291 pp.
- Ulrich, B., R. Mayer and R. K. Khanna. 1980. Chemical changes due to acid precipitation in a loess-derived soil in central Europe. *Soil Sci.* 130: 193-199
- Urban, D. L., R. V. O'Neill and H. H. Shugart, Jr. 1987. Landscape ecology. *BioScience* 37(2): 119-127
- US Environmental Protection Agency. 1976. Quality criteria for water. Publ. No. 440-9-76-023. Cincinnati, Ohio
- US Environmental Protection Agency. 1985. National Air Quality and Emissions Trends Report. US EPA Report No. 450/4-87-001
- US Environmental Protection Agency. 1989. National Air Pollutant Emission estimates 1940-1987. EPA-450/4-88-002. National Air Data Branch, Research Triangle Park, North Carolina

- Vallentyne, J. R. 1970. Phosphorus and the control of eutrophication. pp. 36–43, 49. Canadian Research and Development. May/June. Maclean-Hunter Ltd., Toronto, Canada
- van Breemen, N. and H. F. van Dijk. 1988. Ecosystem effects of atmospheric deposition of nitrogen in The Netherlands. *Environ. Pollut.* 54: 249–274
- Vanek, V. 1987. The interactions between lake and groundwater and their ecological significance. *Stygologia* 3: 1–23
- Vernadsky, W. I. 1944. Problems in biogeochemistry. II. *Trans. Conn. Acad. Arts Sci.* 35: 493–494
- Vernadsky, W. I. 1945. The biosphere and the noösphere. *Amer. Sci.* 33: 1–12
- Vilas County News-Review Staff. 1991. Time stands still in lake country. 17 July 1991
- Vitousek, P. M. 1986. Biological invasions and ecosystem properties: can species make a difference? pp. 163–176. *In*: H. A. Mooney and J. Drake (eds.). *Biological Invasions of North America and Hawaii*. Springer-Verlag, New York
- Vitousek, P. 1990. Biological invasions and ecosystem processes: towards an integration of population biology and ecosystem studies. *Oikos* 57: 7–13
- Vitousek, P. M., J. R. Gosz, C. C. Grier, J. M. Melillo, W. A. Reiners and R. L. Todd. 1979. Nitrate losses from disturbed ecosystems. *Science* 204: 469–474
- Vollenweider, R. A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication, 182. *Water Management Research. Org. Ecol. Coop. Dev. (Paris) Tech. Report DAS/RS1/68.27.* 159 pp.
- Vong, R. J., J. T. Sigmon and S. F. Mueller. 1991. Cloud water deposition to Appalachian Forest. *Environ. Sci. Technol.* 25(6): 1014–1021
- Waring, R. H. and J. F. Franklin. 1979. Evergreen coniferous forests of the Pacific Northwest. *Science* 204: 1380–1386
- Warner, J. S., G. M. Lovett and J. Cadwallader. 1991. Scientists and journalists: A primer for scientists who talk to reporters. *Bull. Ecol. Soc. Amer.* 72(2): 116–118
- Watras, C. J., N. S. Bloom, W. F. Fitzgerald, J. P. Hurley, D. P. Krabbenhoft, R. G. Rada and J. G. Wiener. 1991. Mercury in temperate lakes: a mechanistic field study. *Verh. Internat. Verein. Limnol.* 24(4): 2199
- Webster's Third New International Dictionary. 1968. G+C (George + Charles) Merriam Publ., Springfield, MA
- Wetzel, R. G. 1983. *Limnology*. Second edition. W. B. Saunders, Philadelphia. 767 pp.
- Whittaker, R. H. 1951. A criticism of the plant association and climatic climax concepts. *Northwest Science* 26(1): 17–31
- Wiens, J. A. 1984. The place of long-term studies in ornithology. *The Auk* 101: 202–203
- Wiens, J. A., C. S. Crawford and J. R. Gosz. 1985. Boundary dynamics: a conceptual framework for studying landscape ecosystems. *Oikos* 45: 421–427
- Williams, D. D. 1984. The hyporheic zone as a habitat for aquatic insects and associated anthropods. pp. 430–455. *In*: V. H. Resh and D. M. Rosenberg (eds.). *The Ecology of Aquatic Insects*. Praeger Publ., New York
- Williams, W. D. 1987. Salinization of rivers and streams: an important environmental hazard. *Ambio* 16(4): 180–185

- Winter, T. C. 1976. Numerical simulation analysis of the interaction of lakes and ground water. Geol. Surv. Prof. Paper 1001, 45 pp. Washington, D.C.
- Winter, T. C. 1981. Uncertainties in estimating the water balance of lakes. *Water Resour. Bull.* 17: 82–115
- Winter, T. C. 1985. Approaches to the study of lake hydrology. pp. 128–135. *In*: G. E. Likens (ed.). *An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment*. Springer-Verlag, New York
- Winter, T. C., J. S. Eaton and G. E. Likens. 1989. Evaluation of inflow to Mirror Lake, New Hampshire. *Water Resour. Bull.* 25(5): 991–1008
- Wolin, J. A., E. F. Stoermer and C. L. Schelske. 1991. Recent changes in Lake Ontario 1981-1987: Microfossil evidence of phosphorus reduction. *J. Great Lakes Res.* 17(2): 229–240
- World Resources Institute. 1988. *World Resources 1988–89. An Assessment of the Resource Base that Supports the Global Economy*. World Resources Institute, International Institute for Environment and Development, Washington, D.C. 372 pp.
- World Resources Institute. 1990. *Directory of Country Environmental Studies. An Annotated Bibliography of Environmental and Natural Resource Profiles and Assessments*. Center for International Development and Environment. World Resources Institute, Washington, D.C. 171 pp.
- Wright, R. F., E. Lotse and A. Semb. 1988. Reversibility of acidification shown by whole-catchment experiments. *Nature* 334: 670–675

About the Author and the Book

Professor Gene Elden Likens is the recipient of the ECOLOGY INSTITUTE PRIZE 1988 in Limnetic Ecology. The ECI Jury, chaired by Professor William D. Williams (University of Adelaide, Australia), selected Gene E. Likens primarily for his comprehensive long-term studies of the Hubbard Brook Ecosystem (New Hampshire, USA) which provided a model for ecological and biogeochemical studies worldwide. The study established *inter alia* that rain and snow may be highly acidic. "Acid rain" is now recognized as an environmental hazard in North America, Europe and elsewhere. Likens was elected to the American Academy of Sciences in 1979, and the National Academy of Sciences in 1981. He is the recipient of 5 honorary doctorates.



Gene E. Likens

The book benefits from Gene Likens' unique long-term expertise on ecosystem functions and structures. The author elucidates, with a keen sense of critical, systematic inquiry and ethical responsibility, the instrumentarium of modern ecological research. He explains and documents what it can do. And he outlines what, in his opinion, must be done to avoid, or reduce, human-caused damage to our planet.

About the Ecology Institute (ECI)*

The ECI is an international, not-for-profit organization of research ecologists. Director and scientific staff – 43 marine, terrestrial and limnetic ecologists of outstanding professional reputation – strive to honor excellence in ecological research; to further the exchange among marine, terrestrial and limnetic ecologists; to promote advancement in environmental sciences; and to bridge the gap between ecological science and its application for the benefit of nature and society.

In order to approach these goals the ECI annually sets out two international prizes, the ECI and IRPE (International Recognition of Professional Excellence) Prize, and it supports promising young environmental scientists in Eastern European countries by providing financial assistance for professional travel and scientific equipment. Each ECI Prize Laureate is requested to author a book taking into account ECI's aims and addressing an audience beyond professional boundaries. The book is published in the series "Excellence in Ecology" and made available worldwide at cost price; a considerable number of books are donated to libraries in Third-World countries. In this way leading representatives of modern environmental sciences are offered the possibility of disseminating their personal views on current ecological issues, and of serving the general public who financed their studies in the first place and who depend acutely on definitive ecological knowledge for planning our present and future.

* Nordbunte 23, W-2124 Oldendorf/Luhe, Germany
Tel. (+49) (0) 4132 7127; Fax (+49) (0) 4132 8883