ORNL/TM-9754

ornl

OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

An Investigation of Landscape and Lake Acidification Relationships

Interim Report

R. M. Rush
R. B. Honea
E. C. Krug
R. W. Peplies
J. E. Dobson
F. P. Baxter

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A04 Microfiche: A01

ORNL/TM-9754

Energy Division

AN INVESTIGATION OF LANDSCAPE AND LAKE ACIDIFICATION RELATIONSHIPS

Interim Report

R. M. Rush
R. B. Honea
E. C. Krug*
R. W. Peplies†
J. E. Dobson‡
F. P. Baxter§

*Illinois State Water Survey
†East Tennessee State University
‡Computing and Telecommunications Division
§Tennessee Valley Authority

Date Published—October 1985

NOTICE This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

Sponsored by the
Office of Environmental Analyses
Department of Energy

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

CONTENTS

EXECUTIVE SUMMARY

The focus of this investigation is on the causes of lake acidification—a serious environmental problem. Although acid deposition is generally believed to be the main cause of lake acidification, there is significant evidence that natural processes and landscape changes may also play an important role.

Factors commonly assumed to make landscapes susceptible to acidification by acid rain are also those which enable the formation of acid soils through natural processes. Ecosystem recovery of previously disturbed land is receiving more attention as a possible cause of watershed acidification. Wetlands exert a large influence on surface water chemistry as a large amount of water flows through them, and they are the last portion of the watershed interacting with drainage entering the receiving waters. Indications are present that human interaction in wetland areas may be significant in the lake acidification process. Reforestation and maturation of forests in wetland areas tend to promote the growth of sphagnum mosses which may directly acidify water by ion exchange and by the rapid development of acid humus or peat.

Emmons Pond in northwestern Connecticut is an example of concurrent acidification and landscape change. Land in this area was cut and used for farming during the 1800s. Farming ceased around 1900, and the land began to reforest until at present about 95% of the watershed is forested. Emmons Pond was created about 1934 by damming a small brook. The pH of Emmons Pond has changed from 6.0 in 1963 to a current value of 4.5. Areas of sphagnum moss occur along the stream above the pond. Observation of pH indicates that flow along the stream is initially neutralized (pH 6.1) but becomes acidic (pH 4.3) upon passing through the sphagnum moss areas. Most important, however, is that evidence exists to establish that landscape change may be related to acidification.

While Emmons Pond is an example of the acidification of a specific water body, the landscape/lake acidification relationship is being investigated on a regional basis utilizing remote sensing media along with field trips to establish ground truth. Sixteen lakes in southern New England have been investigated using a Landsat multispectral scanner image and data obtained on a visit to the area. Eight types of vegetation and landscapes that may be related to the acidification processes were identified on the Landsat image. Although sphagnum moss was observed around most of the ponds during the field trips, these areas were not identifiable on the Landsat multispectral scanner images partly because of low resolution. Preliminary investigation of the Adirondack Park area suggest that the higher resolution and additional spectral bands obtained by the thematic mapper instrument may be more effective in identifying key landscape elements. Work is continuing in both of these regions, and for the next phase of this research a thorough testing of the landscape/lake acidification relationship is proposed.

Our general conclusion from these preliminary studies is that there is a landscape and lake acidification relationship and that remote sensing can be useful in investigating this relationship.

ABSTRACT

This interim report presents the rationale and initial results for a program designed to gather and analyze information essential to a better understanding of lake acidification in the northeastern United States. The literature pertinent to a study of landscape and lake acidification relationships is reviewed and presented as the rationale for a landscape/lake acidification study. The results of a study of Emmons Pond in northwestern Connecticut are described and lead to the conclusion that a landscape change was a contributor to the acidification of this pond. A regional study of sixteen lakes in southern New England using Landsat imagery is described, and preliminary observations from a similar study in the Adirondack Mountains are given. These results indicate that satellite imagery can be useful in identifying types of ground cover important to landscape/lake acidification relationships.

1. INTRODUCTION

The acidification of lakes and other water bodies is widely considered to be a serious environmental problem resulting in the loss of fisheries and other aquatic resources. Many investigations attribute this acidification to the deposition of acidic materials from the atmosphere (acid rain) which are generated by anthropomorphic activities (Likens 1976, Mason and Seip 1985, National Research Council 1981). There is also evidence supporting the hypothesis that natural processes and landscape changes may contribute to the acidification of surface waters (Krug and Frink 1983, New York State Department of Environmental Conservation 1982, Patrick et al. 1981, Retzsch et al. 1982, Rosenqvist 1978). The cause of lake acidification (and other environmental damage) is an issue of national concern resulting in proposed legislation to reduce the discharge of acidic materials from sources such as fossil-fueled power generating stations. It is, thus, important to establish the relative roles played by natural and anthropogenic activities in causing lake acidification.

The work reported here is part of a larger effort which focuses on the spatial, historical, and transient dimensions, separately and in concert, of the lake acidification issue and utilizes capabilities in data processing and remote sensing of landscape features that have been developed at the Oak Ridge National Laboratory. This effort is designed to gather and analyze information essential to a better understanding of lake acidification in the northeastern United States.

The work described in this report results from laboratory investigations and field trips to the southern New England and Adirondack Mountains areas. Sixteen lakes in the Connecticut-Massachusetts-Rhode Island area originally investigated by Haines et al. (1983) were visited and the field observations related to Landsat imagery of the same area. A trip was made to the Adirondack Mountains area in New York to observe lakes in the High Peaks region. These investigations are continuing and, therefore, the results reported here are preliminary in nature and do not reflect a complete analysis of the data.

2. RATIONALE FOR PRESENT STUDY

2.1 INTRODUCTION

Acidification of precipitation and surface water to a pH less than 5.6 is commonly attributed to acid rain although there is evidence for the natural occurrence of values below this amount (Charlson and Rodhe 1982, Krug et al. 1985). However, factors commonly assumed to make landscapes susceptible to acidification by acid rain are similar to those that have been observed to bring about the formation of acid soils through natural processes. Acid-soil-forming processes are typically associated with regions that have cool, moist climates. The resultant soils, known as *spodosols (podzols* under the old soil classification system), are generally associated with extensive accumulations of acid organic matter and are underlain by highly siliceous parent material. In their natural state, the resultant *spodosols* are some of the most acidic soils found in the United States, commonly having pH values below 4.

Soils are recognized as highly dynamic landscape elements. Some of their characteristics can "rapidly" change (years to decades) in response to changes in the factors that contribute to their development. Factors recognized as having a profound impact on soil development include climate, biology, geology, topography, and time.

It is well documented that forest clearing for lumber or agriculture reduces soil acidity and alters other aspects of soil chemistry and hydrology. Since the first European settlement, many areas throughout the eastern United States have been subjected to several cycles of clearing and revegetation. Many areas are now reverting to vegetation and increasingly acid soil complexes that are reminiscent of the original landscapes (Goff 1967, Hart 1964, MacConnell 1975, U.S. Forest Service 1982). Biotic recovery from earlier disturbance has recently been given more attention by soil scientists in regard to acidification of watersheds (Krug and Frink 1983, Rosenqvist 1978, Skartveit 1981, Troedsson 1980).

The view that acid rain is the only cause of the acidification of lakes may not be scientifically valid. There is evidence (Krug and Frink 1983, Retzsch et al. 1982, Duhaime et al. 1983), that in many cases lake acidification may result from a combination of natural acid-soil-forming processes and anthropogenic acid rain. Furthermore, it is suggested that natural acid-soil-forming processes may be the principal causative factor and can be directly related to the historical landscape changes that have occurred in the watershed. In fact, evidence exists that some waters may have always been acid and had fisheries problems (Pfeiffer and Festa 1980, Patrick et al. 1981), although acid rain is undoubtedly contributing to acidification.

Indeed, earlier reviews further support the view of natural acidification and fisheries problems, showing that the Adirondack and inland waters of New England have had failures of natural fish populations and stocking programs that date back at least to the early 1900s (Smallwood 1918, Kendall 1924, Johnson 1927). Those factors thought to be influencing fisheries were stated to be the natural unsuitability of waters, activities of man, and the reintroduction of the beaver.

Kendall (1924, pp. 262–63) further elaborated on one water quality factor. "In addition to pollution to which reference has been made there are conditions which may be called natural pollution ...; there is one condition in particular that should be mentioned. It is concerned with acidity of water." He notes that bog waters (particularly from sphagnum bogs), floods after droughts, and spring snowmelts are especially acid, resulting in the coagulation of fish mucus.

At the same time, Dahl (1927) noted that

> For a considerable time trout and salmon hatcheries in southwestern Norway found themselves confronted with grave difficulties in rearing .... The waters of that region are obviously very acid, and very small alterations in the acidity may be sufficient to render them acid to a degree dangerous to fish life ... variations in acidity occur according to seasons or according to the rainfall .... It is also well known that a number of apparently fine forest brooks in this region of woods and peat bogs are and always have been entirely devoid of trout .... We know that the soil of this granite district is very acid .... There is every reason for study of the subject [the survey and correlation of soil and water].

The statements of Kendall (1924) and Dahl (1927) belie the commonly held belief that transient acid runoff events and associated fish kills are strictly acid-rain-related phenomena. Recently, Noggle et al. (1984) showed that leachate from acid soil was the probable cause of a fish kill involving rainbow trout. They suggest that the organic acids in some soils have an adequate buffering capacity to be relatively unchanged by inputs of acid from the atmosphere. They concluded that the 50-fold increase in hydrogen ions and the 7-fold increase in aluminum ions which they observed in runoff water or in water collected from special lysimeters was principally caused by the release of ions from the uppermost acid soil horizons during storm events. Water which had come in contact with less acid subsoils and underlying geologic materials was not toxic to fish, nor did it have high levels of aluminum ions.

While literature exists regarding natural acidification and hydrologic processes, little research has been done to examine the relative effects of acidification by natural processes and those effects caused by acid rain, particularly in the context of the spatial and temporal variations of the problem. The following sections briefly discuss some of the literature.

2.2 MAN-INDUCED CHANGES OF LAND COVER AND SOILS

Of the five interactive soil-forming factors—climate, biology, geology, topography, and time—man has definitely influenced climate (i.e., chemically through acid precipitation). He has also affected the factors of time and biology by repeatedly disturbing the natural forested landscape through clearing, cutting, and burning. In recent years, however, forest recovery from this earlier disturbance has been pronounced. U.S. Forest Service statistics (1982) indicate that standing wood is increasing faster than the removal rate by cutting and mortality, so that, in the New England, Mid-Atlantic, and Great Lakes states, the volume of standing wood increased by 61.4% between 1952 and 1977.

While on an overall basis these increases are shared equally between conifer (softwood) and deciduous (hardwood) species, there are differences by region and state. For example, the volume of standing wood is increasing faster on a percentage basis for hardwoods than softwoods in the mid-Atlantic states. This large increase in hardwoods reflects the recovery of forests in Pennsylvania, which has the greatest volume of hardwood of any state in the country (Powell and Considine 1982). The overall increase also reflects the early action taken by New York to preserve the Adirondacks, which contain much of the softwood in the area.

Forest recovery in the Adirondacks is more advanced than in other areas. Therefore, the percent increase is low even though only about 40,000 hectares of commercial forest land in the total 2.4-million-hectare region has not been cut over (Marshall 1925, Thompson 1962).

The forests of the southern New England states (Massachusetts, Connecticut, and Rhode Island) are principally hardwoods, and the volume of standing wood in these states increased by more than 100% between 1952 and 1977. In New England as a whole, however, softwood volumes have been increasing faster than hardwoods because Maine's forests are principally composed of spruce and fir, and the volume of spruce and fir increased two to three times that for all other types between 1959 and 1971. This rapid increase is attributed, in part, to the recovery from budworm attacks and from fires induced by man even though spruce and fir are the mainstay of the state's paper industry (Ferguson and Kingsley 1972).

For New Hampshire and Vermont, it has been estimated that between 0.4 and 0.8-million hectares of the original spruce and fir forest have been converted to hardwood forest because of fire, lumbering, and farming (Lull 1959, Hart 1964). Apparently the softwood tree species are reclaiming the land, however, because the area of spruce-fir forest in New Hampshire nearly doubled between 1949 and 1960, reaching a total of around 0.45-million hectares in 1960 (Ferguson and Jensen 1963). In addition, Kingsley (1977) noted that spruce-fir acreages in Vermont had increased 18% to a total of 0.32-million hectares in 1973.

One conclusion readily apparent from this review is that eastern forests have been in a constant state of change for several decades. Any assessment of acid rain impacts should take this fact into account.

2.3 EFFECTS OF LAND COVER CHANGE ON WATERSHEDS

Recovery and maturation of a forest from disturbance is usually accompanied by the accumulation of organic matter and acids in the forest floor and upper mineral soil horizons. This phenomenon tends to be especially pronounced under conifers and in "sensitive" landscapes that naturally accumulate large amounts of acid organic matter, such as those found on steep and rocky landscapes or in wetland areas (Krug and Frink 1983, Heimburger 1934, Troedsson 1980).

The chemistry of increasingly acid soils results in naturally acid solutions (hydrogen and aluminum ions) in those soils. It is possible that this change in chemistry also changes the chemical interaction of acid deposition with the landscape. As soils become more acid, the percentage of exchange sites occupied by cations (percent base saturation) decreases, and bases become increasingly harder to displace by acid additions (Wiklander 1973/74, 75; Seip 1980). Acid soils may, thereby, be increasing the proportion of hydrogen and aluminum ions leached by mobile anions (e.g., sulfate) of acidic deposition. On the other hand, concomitant increases in organic acids in soil materials may be increasing the rate at which hydrogen ions in precipitation immobilize organic acids and complexes that leach hydrogen ions and other ions. Thus, rates of cation leaching may not be proportional to increased rates of sulfate leaching (Krug and Frink 1983, Krug and Isaacson 1984, Krug et al. 1985).

Furthermore, development of forest canopy through reforestation generally reduces snow throughfall and also results in snowpack persisting longer into the spring, resulting in more frequent episodic runoff events when warm weather and warm rainfall occur (Connaughton

1935, Lull and Rushmore 1960, Schneider and Ayer 1961, Eschner and Satterlund 1963, Satterlund and Eschner 1965, Harr 1981). The relationship between spring snowmelt and acidic runoff may be becoming more pronounced partly because of the changes in hydrology and chemistry induced by changes in the forest landscape. Although it has been suggested that spring snowmelt may result in slugs of acidic runoff being introduced into adjacent waters, recent results from studies conducted by the U.S. Forest Service personnel in the Sierra Nevada Mountains indicate that pH levels may actually increase with spring snowmelt. Their conclusion is that the level of pH in snowmelt runoff is more a function of the distribution of the various types of soil adjacent to streams than levels of acid deposition built up in snowfall (Berg 1985).

2.4 WETLANDS FORMATION RESULTING FROM LAND COVER CHANGE

Wetlands exert a disproportionately large influence on surface water chemistry as a large amount of water flows through them, and they are the last portion of the watershed interacting with drainage entering the receiving waters (Braekke 1981, Everett et al. 1982, Krug and Frink 1983). Disturbance and recovery of wetland ecosystems may play a significant role in the lake acidification process.

The identification of wetland areas is often done with remote sensing media (Heinselman 1963, MacConnell 1975, Sims et al. 1982). Using aerial photographs, Mueller (1974) has already shown that a large-scale successional change of open wetland to wooded swamps occurred in Massachusetts during the 1951-71 period. The fact that wetlands can be identified with remote sensing media is important, because wetlands, soil types, and water chemistry correlate well with ecosystem types (Jewell and Brown 1929, Kurz 1929, Sjors 1950, Gorham 1956, Gorham and Pearsall 1956, Heinselman 1963, Jeglum 1971, Verry 1975, Schwitzer 1978, Hemond 1980, Patrick et al. 1981, Sims et al. 1982, Karlin and Bliss 1984). These studies indicate that Landsat imagery or other appropriate remote sensing media may provide a convenient mechanism to inventory landscape types in relation to impacted water bodies.

An examination of the history of settlement in the northeast indicates that man's disturbance of wetland areas has been pervasive. Wetlands were among the first areas to be cut over, and they have been repeatedly disturbed (Fox 1902, Chittenden 1905, Defebaugh 1906 and 1907, Hawley and Hawes 1912).

Cyclical changes in climate and other natural variations in the environment can also influence the extent and regional distribution of wetlands. For example, the last 40 years have been considerably wetter than the preceding 40 years for the Great Lakes and Adirondack regions (Quinn 1981) and expansion of sphagnum wetlands in the Adirondacks due to increasing precipitation has been suggested (Duhaime et al. 1983).

The reintroduction and protection of the beaver just after the turn of the century has also resulted in a considerable increase in beaver ponds and adjacent wetlands in the Adirondacks (Johnson 1927, Eschner and Satterlund 1966). MacConnell (1975) estimated that the reintroduction of the beaver caused the formation of at least 970 hectares of beaver ponds and an unspecified amount of wetlands between 1951 and 1971 in Massachusetts.

Changes in wetlands may have profound effects on water chemistry and hydrology. Reforestation and maturation of forests in wetland areas tends to promote the growth of sphagnum mosses (Shaler 1890, Tiurin et al 1935, Rigg 1940, Tamm 1950, Marbut 1951, Lag 1959, Ugolini and Mann 1979). It is known that these mosses, and others, directly acidify water by ion exchange and also by the rapid development of acid humus or peat. This relatively rapid development of peat impedes the local drainage and results in further expansion of wetland areas (Shaler 1890, Rigg 1940, Tamm 1950, Marbut 1951, Viro 1974, Ugolini and Mann 1979, Glaser 1983). Less well known is the fact that the roots in the forest itself acidify peat through plant-ion-exchange and the creation of organic acids (Williams et al. 1978).

Highly acid sphagnum mosses and related plant communities can develop in the area adjacent to newly created wetlands areas (Swan and Gill 1970, Andreas and Host 1983). In fact, Krug has noted that many sphagnum bogs and lawns in Connecticut have developed in association with abandoned beaver ponds and impoundments and that these areas now extend well into abandoned farm fields. Water is acidified as it flows through these areas. The extent to which this type of landscape change is a widespread phenomenon relative to lake acidification is an important question.

The above review strongly suggests that wetlands are an important factor in landscape/water acidification relationships which merits further study.

2.5 OBSERVATIONS AT EMMONS POND

2.5.1 Watershed Description and History

Emmons Pond lies in Hartland, Connecticut, in the northwestern part of the state, 2.5 km south of the Massachusetts border: latitude 42° 00′ 56″ N, longitude 72° 54′ 50″ W, elevation 334 m (Fig. 1). The pond has a surface area of 3 hectares, mean depth of 1.0 m, and an estimated mean flushing rate of 22 days. Its 75-hectare watershed lies at the edge of a dissected plateau. The watershed is well defined by low ridges created by erosion along directions of dip and strike of the Hartland schist bedrock. Total relief is less than 50 m. Except for the sides of the ridges, slopes are mostly gentle, 3 to 15%. Most of the watershed is covered by 3 to 5 m of highly permeable gravelly sand till of local origin. Tills on the ridges are shallow and compact.

Bedrock of the Emmons Pond watershed is metamorphosed, iron-rich, pelagic marine sediments, nearly all of which is Hartland schist. The schist is generally quite uniform, as indicated by its having been mined locally to produce earthenware.

Over 90% of the watershed has been in agricultural use and has probably been cropped or grazed for over a century. Hartland was settled in 1753. Its early industries were related to agriculture and forestry. Forestry-related industries declined as forest was lost to a rapidly growing agricultural community whose population peaked at 1318 in 1800. Subsequently, Hartland's population declined to a low of 296 in 1929 and remained constant until after the Second World War. The out migration occurred in two waves: 1800–1850 and 1900–1930. Most of the farmland in the Emmons Pond watershed was abandoned around 1900. The state began acquiring abandoned land in 1923. Today half of the watershed is in Tunxis State Forest and 95% of the watershed is forested.

In the early 1900s the remaining population, which was still largely agricultural, relocated along major roads, and previously abandoned agricultural land began reverting to young forest (see Appendix A, Fig. A.1). The rural agricultural nature of Hartland ended

ORNL–DWG 85-10652

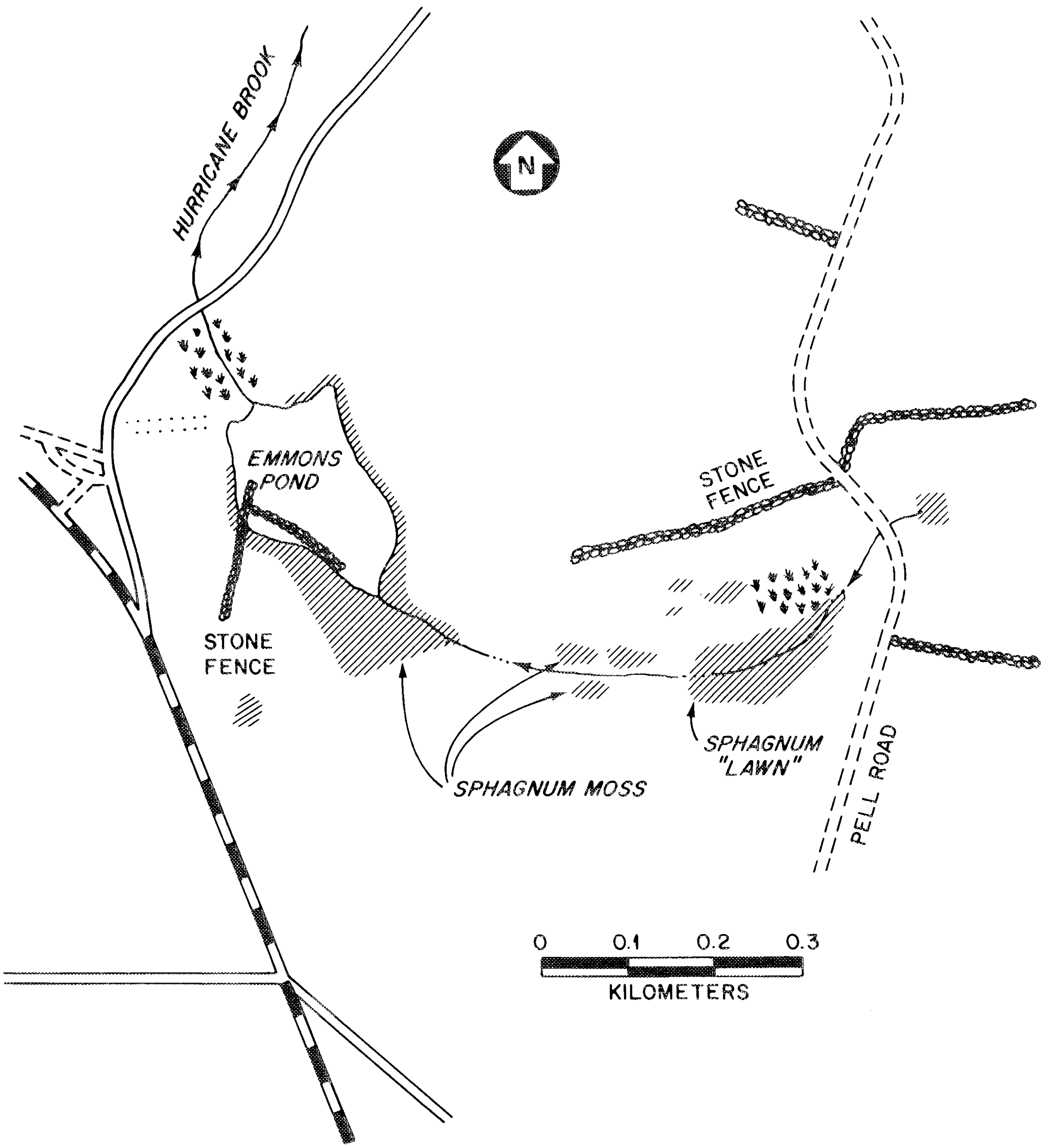

Fig. 1. Emmons Pond area.

along with the Great Depression. The post-Second World War population boom was in rural, nonfarm population resulting in very little area of land used per unit population (Fig. A.2).

The Civilian Conservation Corps (CCC) created Emmons Pond between 1930 and 1934 by erecting a low earthen dam across Hurricane Brook along the lines of a road abandoned sometime after 1911. Much of the land flooded by the dam was agricultural, as evidenced by two stone fences running along the bottom of the pond. A spillway was added to the dam because of flooding damage from the 1938 hurricane. Part of the pond was dredged out.

The CCC intensively managed the local forests and was probably responsible for the current healthy condition of the northern hardwood forest. A number of fire control waterholes were dug out in moist sites and 10% of the Emmons Pond watershed had red pine planted on agricultural land abandoned in the 1930s.

Emmons Pond was managed as a fishing pond until 1974. The pond was noted for its largemouth bass and very large eastern chain pickerel. Decline in fishing quality corresponded to the discontinuance of the practice of winter drawdown as a control of aquatic vegetation. In 1974 the outflow pipe was jammed and this, along with colonization by beaver, resulted in raised water levels. By 1975 water lily ringed the pond and, along with submerged vegetation, completely choked the pond within several years. Local accounts noted that when the pond became choked with weeds, its sediments began giving off putrid-smelling "sulfur soda." Evolution of hydrogen sulfide is probably attributable to anoxia in sediments induced by aquatic vegetation greatly reducing mixing while increasing deposition of organic detritus. Within one year after the water level was raised, sphagnum moss began growing around its edges and trees in these now-moist areas began dying. Most of the dead trees were cut for firewood in 1978–81.

Areas of sphagnum moss occur at several places along the stream above Emmons Pond (Figs. 1 and 2) and acidify this main water supply of the pond (Fig. 2). The area of primary interest is the sphagnum "lawn" area in Hurricane Brook just west of Pell Road (Fig. 1). Evidence suggests that this sphagnum lawn developed rather recently. Sphagnum mosses are a prolific species that develop into peat. The absence of peat in these areas also indicates that the sphagnum is of recent origin. The low-lying land along the stream experienced a period of severe erosion. Severe erosion from flash floods is indicated by an approximately 5-cm layer of muck overlaying essentially pure gravel and coarse sand. The deltaic formation at the mouth of the stream indicates that this event occurred since the creation of Emmons Pond and probably from the hurricanes of August 1955. The muck is overlain by a 7–8-cm layer of partially decomposed litter mixed in the uppermost centimeter with some remains of sphagnum which represents the transformation from the scoured flood plain to forest floor to a sphagnum-dominated cover. This layer is, in turn, overlain by 5 cm of

ORNL-DWG 85-10653

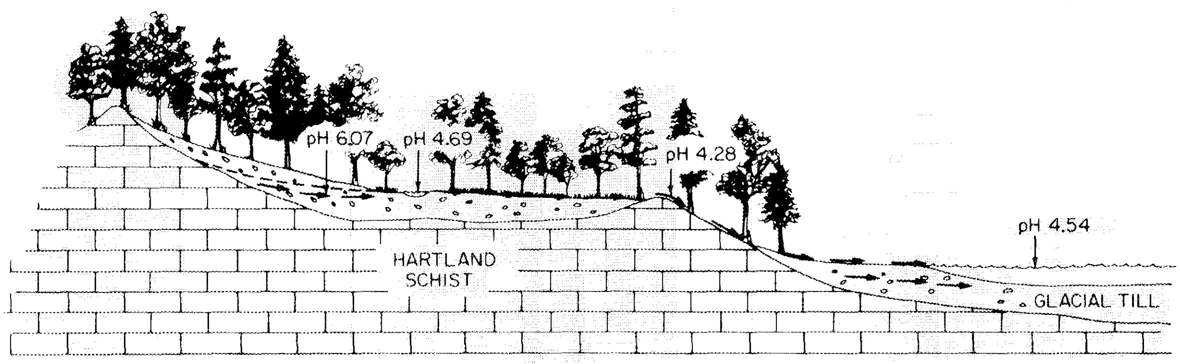

Fig. 2. Cross-section of the Emmons Pond area.

dead and decomposing sphagnum interspersed with seven thin layers of leaf litter as of the summer of 1983. This suggests a 7-year period of a sphagnum-dominated wetland community. Finally, there is a 5-cm layer of living sphagnum moss. This sphagnum lawn has expanded out beyond the central flood-scoured wetland area over the last several years. Other sphagnum lawn areas along the stream appear to be of even more recent origin.

It is possible that sphagnum lawns existed in the headwaters of Hurricane Brook prior to the floods of 1955 and that Emmons Pond was previously acid. Historic acidification, however, is related to proliferation of sphagnum after the drought of the 1950s and 1960s ended. Given the present condition of the watershed, established sphagnum has been able to survive drought years such as 1978, 1980 (the year the U.S. Fish and Wildlife Survey sampled Emmons Pond), and 1981 (Fig. 3).

ORNL-DWG 85-10651

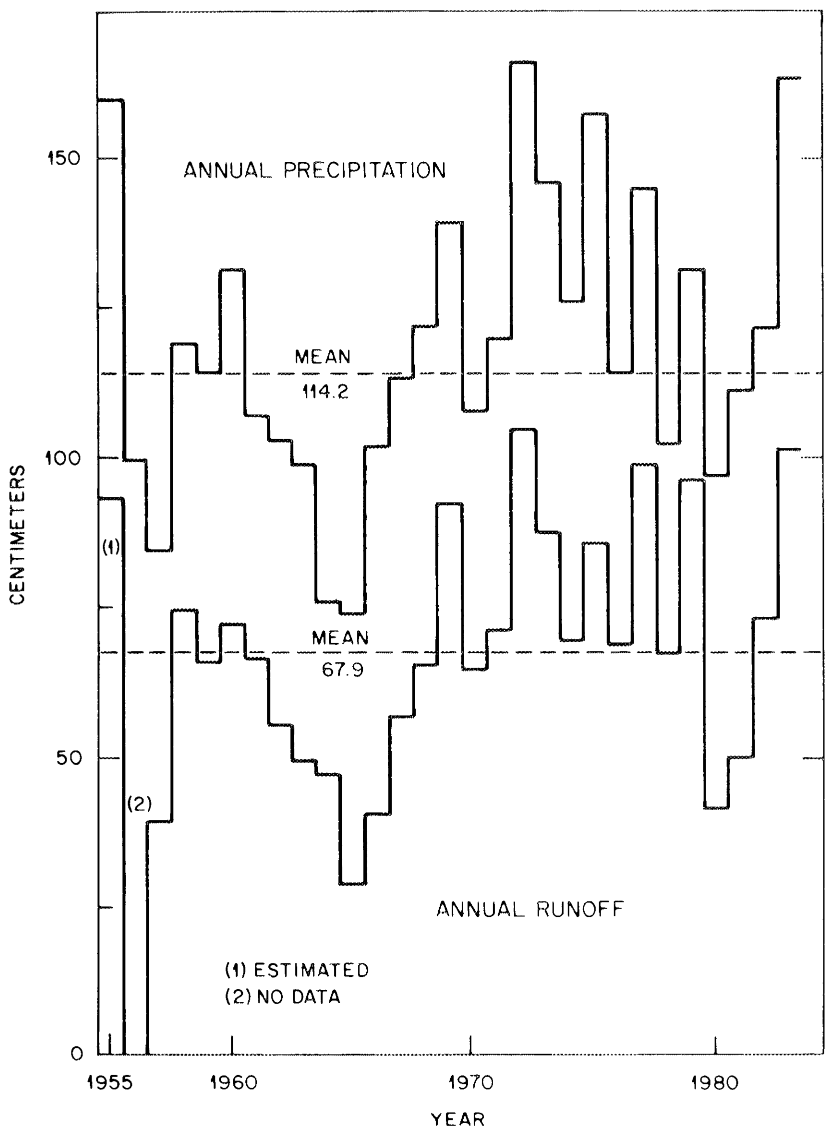

Fig. 3. Annual precipitation and runoff at Barkamsted Reservoir, Connecticut, for 1955 to 1983.

2.5.2 Present Investigation

A detailed study was made of Emmons Pond to assess acidification/watershed interactions. The watershed is small (75 hectares), well defined, and hydrologically simple.

Emmons Pond is one of only 19 critically acid (pH < 5) waters found in the regional survey of New England headwaters (Haines et al. 1983). It is unique in that both water chemistry modeling and historic water quality data indicate marked acidification over the last two decades. Emmons Pond had a mean pH of 4.54 during a 15-month study by Krug. Application of Henriksen's model (Hendriksen, 1979) to Krug's mean water chemistry data estimated the pre-acidification pH to be 5.84. Historic pH values for single sampling dates were 5.8 in 1960 (ACID database) and 6.0 in 1963 (Haines et al. 1983). The U.S. Fish and Wildlife Survey (Haines et al. 1983) reported an average pH of 4.60 for a single sampling date in 1980.

The acidification of Emmons Pond defies conventional wisdom. First of all, acidity of precipitation has apparently not changed much over the period of interest. Precipitation at Windsor (48 km SE) had a mean pH of 4.2 from 1929 through 1948 (Frink and Voigt 1976). The weighted annual average pH of precipitation in the area was 4.5 for 1955–56, 4.3 in 1965–66 (U.S. Department of Energy 1983), and 4.3 in 1982 (Interagency Task Force on Acid Precipitation 1983). Second, the pond receives most of its water from the drainage basin. Thus, acidification of the pond directly by acid deposition is slight as Emmons Pond occupies only 4% of the watershed. Likewise, wetlands occupy only 6% of the watershed. Virtually all of the watershed is gently sloping (3–15%) and mantled by 3–5 m of highly permeable gravelly sandy till. Consequently, acid deposition has ample opportunity to be neutralized.

Indeed, nearly all precipitation falling in the watershed is neutralized to around pH 6 (Fig. 2). However, Emmons Pond is principally fed by emerging groundwaters that form the headwater of Hurricane Brook (Fig. 1); this water is re-acidified by plant ion exchange as it passes through sphagnum moss enroute to the pond (Figs. 1 and 2).

This discussion covers only a portion of the analysis of Emmons Pond and is included here to illustrate a case study that supports the hypothesis that landscape changes may play a role in the acidification process. Additional detailed chemical and hydrologic data will be presented in a separate publication dealing specifically with the acidification process at Emmons Pond.

2.5.3 Conclusion

The observations presented suggest that reforestation in the area of Emmons Pond and the associated development of areas of sphagnum moss above the pond are the main cause of the acidification. The presence of sphagnum contributes to the acidification in two ways: first, by direct addition of hydrogen ions by ion exchange and, second, by supplanting or overriding other processes which tend to increase pH. While this is probably not the sole cause of the acidification of Emmons Pond, the evidence is sufficiently clear to establish landscape change as being related to the acidification.

3. REGIONAL STUDIES

3.1 INTRODUCTION

Landscapes are highly dynamic and, at a regional level, change in response to macroscale cultural and physical processes such as economics, technology, and climate. In contrast, local landscapes change in response to site-specific phenomena such as the landowner's preference for agriculture, grazing, forestry, or recreation. In combination these macro and microscale dynamics create an ever changing stage for biochemical changes in soil and water characteristics—a stage that can vary dramatically over time and space. While it is clear that lake acidification also varies in time and space, at present there is insufficient evidence to clearly establish a spatial or temporal correlation or causal relationship on a regional scale between landscape change and lake acidification. The research design of this study is intended to develop, over time, the data and information necessary for stochastic testing of possible correlations. In the absence of significant data for a quantitative analysis and because this is an interim report, a regional approach with site-specific analysis of selected watersheds has been employed in southern New England and in the Adirondack Mountains region to examine the landscape/lake acidification issue.

3.2 RELATIONSHIP TO EMMONS POND

The geology of the Emmons Pond area (described in Sect. 2.5) is similar in many respects to the areas examined in the regional study of southern New England. The watersheds examined in Connecticut, Massachusetts, and Rhode Island are generally located on Precambrian granitic, igneous, and metamorphic bedrock mostly overlain by sandy glacial till of local origin. Most of the lakes are in headwater locations. However, surface configuration varies by watershed; some exhibit undulating to rolling terrain, others are moderately sloping with exposed bedrock within the watersheds. In general, vegetation contrasted greatly among the watersheds within the study area. Most importantly, it was evident that many of the watersheds had experienced changes from agricultural uses to largely a forest cover similar to the Emmons Pond watershed. Some of the terrestrial ecosystems show definite impacts of man, whereas others appear more natural, but nevertheless show some evidence of being influenced by human activities.

Human impact (past and present with respect to all of the southern New England lake area watersheds examined) is especially pronounced. Contrary to reported documentation, none of the areas are isolated and undisturbed. Many of the watersheds are criss-crossed with stone fences which in the past enclosed large and small fields, indicating that agriculture was a dominant activity in the past. In a few situations, sections of the watersheds are still being used for low-intensity farm purposes; but at the present time, the majority of the watersheds show evidence of being used for recreation purposes. In addition, most lakes and ponds have been dammed.

Thus, in many general aspects (except for the variation in macro vegetative structures and topographic forms), Emmons Pond is representative of the lakes studied in southern New England. And it is apparent that most lake watersheds have undergone the same, or at least similar, successional changes.

3.3 APPROACH

3.3.1 Conceptual Approach

From the Emmons Pond study, it is clear the ideal approach would be to conduct thorough historical analyses of numerous lakes and their upstream basins and to investigate spatial and temporal correlations among landscape, vegetation, soils, and lake chemistry. Unfortunately, it was impractical within the scope of this study to repeat the intensive effort devoted to Emmons Pond for even a few lakes. The resulting sample would have been far too small to quantitatively investigate the variety of causal relationships that must be studied.

At the opposite extreme, extensive data bases are being developed for hundreds of lakes as part of the National Acid Precipitation Assessment Program and other studies. Unfortunately, none of the currently published data bases capture the landscape elements that are most likely to influence natural acidification processes. Land use data have been collected for many lakes, but land use is an economic and cultural concept that reveals little about key physical features such as the age and composition of a forest, the depth of humus on a forest floor, the extent of sphagnum lawn development, or the nature of biochemical processes in soils and water.

The conceptual approach adopted in this study lies between the two extremes previously described. In general, the approach is to develop and analyze a data base of moderate size for numerous lakes. The data base focuses specifically on landscape elements which may be related to natural acidification processes. The study also relies on existing data bases, such as ACID (Hendry et al. 1983), for additional information on lake chemistry. Data base development is accomplished through remote sensing, examination of historical documents, and site visits.

3.3.2 Remote Sensing Analysis

An important objective of this project is to investigate the potential of Landsat spectral data to aid in identifying landscape elements which may influence lake acidification. Digital remote sensing from satellites offers the advantages of synoptic, large area coverage and frequent, repetitive observations, but there are disadvantages as well. Satellite observations go back only to 1972; further historical analysis requires additional information from sources such as soil surveys, wetlands inventories, maps, aerial photographs, and written documents.

Although Landsat tapes are available for all of the regions of interest, practical considerations of time and cost limited this preliminary investigation to a single multispectral scanner (MSS) scene in southern New England and single MSS and thematic mapper (TM) scenes in the Adirondacks. This constraint prohibited remote sensing analysis of Emmons Pond in the southern New England study—a step which would have been highly desirable for comparative analysis. The scene containing Emmons Pond will be available in the near future. The Adirondacks scene covers the northeast quadrant of the Adirondack Park and includes the acid lakes of the High Peaks area. Unfortunately, it does not include the large concentrations of acid lakes at lower elevations in the western Adirondacks. It will be essential to remedy this deficiency in future work.

The approach in southern New England involves the interpretation, classification, and analysis of MSS data for a study area in eastern Connecticut, Rhode Island, and eastern Massachusetts (Fig. A.3). Sixteen lakes were selected from among those in the Haines study (Haines et al. 1983) for detailed analysis, including Landsat classification, site visits for ground truth and pH checking, and spatial analysis of pH data relative to vegetation and land cover data. MSS data for October 31, 1978, were used in the initial test. The test was conducted in the following steps:

1. Tentative land cover classes were determined on the basis of supervised training samples in areas of known land cover.
2. These classes were checked with information available from other sources such as 1:24,000 USGS topographic maps and some additional land use information interpreted and mapped from low altitude aerial photography by the University of Massachusetts.
3. Investigators visited each lake, its immediate drainage basin, and additional sites for field verification of the tentative classes and for collection of additional ground truth.
4. Land cover classes were determined again through iterative refinement of supervised training samples.

The results of this procedure are encouraging in that the MSS data appear to be capable of distinguishing certain types of vegetation and land cover that may be related to acidification processes. In particular, the identification of water bodies and wetlands appears to have a high degree of accuracy, which is particularly crucial for those vegetative types that are characteristic of spodosols (podzols), muck, and decaying organic materials that may contribute significantly to the acidification processes. Field work indicates that separate and reliable signatures have been established for:

1. water bodies including ponds, reservoirs, sea water, and standing water in swamps;
2. vegetated water including ponds with high concentrations of floating vegetation and bogs with water seasonally encroaching into low brush;
3. forested swamps;
4. deciduous forest;
5. coniferous and mixed coniferous/deciduous forest;
6. late season grains;
7. urban buildup and residential lands; and
8. open fields including pastures, grasslands, and fallow fields.

The only significant anomaly discovered in the classified images so far is the fact that the forested swamp signature is very similar to the signature of a type of vegetative land cover in one local area in eastern Massachusetts which has resulted from stress and die back of coniferous forest affected by insects and diseases. Attempts to identify sphagnum lawns and to identify any distinguishing characteristics of water bodies indicative of pH were unsuccessful using the MSS data. It is hoped that use of higher resolution TM images will be more successful.

The Landsat analysis was conducted on an International Imaging Systems model 70 image processing system (system 500) in the Oak Ridge Geographics Laboratory. The Landsat IV scene (path 13, row 31) of southern New England was examined extensively, and portions of the scene were studied in great detail.

3.4 SOUTHERN NEW ENGLAND TEST SITES

3.4.1 Introduction

The field, "ground truth," task was carried out during the weekend of September 22–23, 1984. Two field teams were involved to verify the spectral signatures gained from the initial classification effort. In all but two of the ponds investigated there were varying areas of sphagnum moss or herbaceous wetland vegetation. Although no quantitative measurements were made, it was noted that lake acidity and amount of sphagnum lawn or herbaceous wetland were positively correlated (Table 1). The two exceptional areas which had low pH's (Little College and New Long ponds) were located in eastern Massachusetts in an area of dead conifers.

3.4.2 Acidity

The pH values for lakes examined in southern New England were, in general, relatively high. Six of the 16 headwater lakes had pH values which averaged greater than 6; four had values between 5 and 6; and the remaining six lakes had pH values less than 5. For one lake—Wilbur—the average pH was less than 4.

It was subjectively noted that, in general, the amount of sphagnum moss within a watershed was inversely related to the pH. However, it is recognized that such an evaluation is, at best, a "guesstimate," and a more accurate evaluation would depend on other factors which are measured in a more precise manner. Nevertheless, even with this cursory inspection, there were no suggestions of opposite situations being true.

3.4.3 Vegetative Cover

Forest communities are the dominant cover within the watersheds of the inspected lakes. In none of the situations inspected was the forest cover original; all showed signs of being cutover, and in some cases the cutover sections were of recent origin. In a majority of watersheds, some forest cover was enclosed by stone fences, indicating that the land had been used for agricultural purposes. The fences, however, were old and in various states of disintegration, indicating that the land may not have been used for agricultural purposes for some time.

The tree species in the forest varied; some were coniferous and some were deciduous. Red maple, ash, alder, and white cedar dominated in the wetter soil regions. The lower strata were dominated by sweet pepperbush, blueberry, viburnum, cinnamon fern, and royal fern. Sphagnum and other mosses were located in some of the wetter regions. With the exception of Carr and Whitmans ponds, it was observed that as "sphagnum lawns" developed they were associated with an opening in the canopies. It appears that some of the trees tended to be killed off as the sphagnum lawns grew.

Conifers tended to occupy upland and drier sites. The dominant conifer encountered was the eastern white pine; however, in isolated locations spruce and hemlock were found. Where

Table 1. Ponds investigated in southern New England

Pond	Latitude[a]	Longitude[a]	Mean pH[a]	Remarks
				Connecticut
Clubhouse	41°41′59″	72°24′28″	6.42	Lake cover with vegetation; much of the drainage area open land.
Darling	41°48′18″	72°07′35″	6.05	Lake fully covered with floating vegetation; surrounded by moss areas.
Norwich	41°23′11″	72°18′13″	6.70	Lake used for recreation purposes; little moss.
Uncas	41°22′26″	72°18′52″	6.82	Same as Norwich.
Whitmans	41°58′48″	71°48′11″	5.01	Extensive areas of moss in drainage basin; significant amount of vegetation in the lake.
				Massachusetts
Johns	41°55′07″	70°50′35″	5.02	Coniferous forest and cranberry bogs in watershed; clear water.
New Long	41°52′56″	70°41′49″	5.45	Medium size conifers, many killed by disease and replaced by low brush, clear water; limited drainage area; no evidence of moss.
Little College	41°54′18″	70°41′05″	4.38	Tall conifers, many killed by disease and replaced by low brush, clear water; limited drainage area; no evidence of moss.
				Rhode Island
Carbunkle	41°41′58″	71°41′28″	6.14	Large drainage area, limited amount of moss in drainage area.
Deep	41°23′26″	71°39′46″	5.80	Fed by Schoolhouse Pond with large swamps in watershed; clear water.
Ell	41°30′00″	71°46′28″	4.29	Extensive area of moss in drainage basin, water covered with vegetation.
Long	41°30′00″	71°46′19″	4.63	Water clear of vegetation and drainage area without moss; lake connected to Ell Pond. This is a stratified pond with pH=4.37 at surface and pH=5.38 at 6 meters.
Sucker	41°56′13″	71°40′00″	6.79	Some wetlands and moss in drainage basin; much open land.
Carr	41°38′09″	71°33′18″	4.72	Abundant sphagnum and ferns in watershed; bogs at mouth of source stream, clear water.
White	41°24′53″	71°32′43″	4.41	Areas of wetlands and moss in drainage basin.
Wilbur	41°55′50″	71°45′43″	3.98	Extensive areas of wetlands and moss in drainage basin; water relatively clear of vegetation.

[a]Source: Haines et al., 1983.

these latter two conifers were found, there were also some tendencies toward the development of distinctive albic and spodic soil horizons.

A distinctive vegetative community change occurred in the coastal plain. Here, although the varieties of trees were basically as they were in upland locations, there were increases in low-growing sedges, reeds, and grasses, including smartweed, wild mullet, wildrice, saltgrass, and cordgrass.

In eastern Massachusetts, large areas of eastern white pine were observed. Often these conifers were located on higher and drier areas, which were removed some distance from a peat bog. Peat bogs in these areas were frequently converted to agricultural uses, particularly cranberry bogs.

3.4.4 Terrain and Geology

All of the watersheds inspected had been covered by glacial ice sheets in their recent geologic past. In some locales there was evidence of ice scouring; however, the majority of the area underwent glacial deposition. In general, upland till plains were the most extensive glacial till encountered. The till was mostly from granitic, schistic, and gneissic rocks. Glacial stones and boulders were commonly scattered on the surface of these plains, and bedrock outcrops were apparent in several locations. In most watersheds inspected, the glacial till was loose and unconsolidated. Frequently, the texture of the till was sandy and/or angular, gravel-like in texture and particle-size. The coastal area was characterized by glacial outwash deposits which contain stratified materials some of which are compact and clayey.

The surface configuration of the majority of the watersheds inspected consisted of low-relief features. In a few situations, the watershed drainage boundary was difficult to discern in the field or on topographic maps. The majority of lakes in the watershed measured a few hectares to a few tens of hectares; none were large. The watershed size is correlated with lake size, but the smallest lakes frequently had the most diverse surface configurations within their respective watersheds.

3.4.5 Drainage and Hydrology

All of the lakes field inspected in the southern New England area were located in headwater areas. This was one of the criteria used originally to select these lakes for incorporation in the Haines study (Haines et al. 1983). Fourteen of the sixteen lakes were fed by first- or second-order streams. At least two of the lakes were fed mainly from underground sources, with no apparent surface drainage system. All of the lakes had some stream outflow, although many of these were dry at the time of field inspection; it was apparent for some of the lakes that a portion of the outflow was via underground aquifers, especially those with sandy beds.

A major differentiating distinction among the lakes was the amount of aquatic vegetation. Shallow, small, and old lakes (some of the lakes obviously were recently created by damming since they were not present on recent topographic maps) had varying amounts of vegetative growth. One lake was completely covered with water lilies, and it was difficult to distinguish water from vegetation in the Landsat pixel which represented this lake. Other lakes of this category had some portion of the surface area which was clogged with floating aquatic plants. All of the lakes with floating vegetation also display some submerged species, especially so for lakes less than 2 m in depth. Most of the deeper lakes have submerged aquatic vegetation visible along the shorelines. Because of organic matter in the waters, depth, or surface waves, the field teams were unable to verify the existence of submerged vegetation in the larger and deeper lakes. None of the lakes, however, showed evidence of aquatic "dieback." Persons interviewed who lived in the vicinity of the lakes inspected were not aware of any fish kills or other similar events which have been characteristic of other lakes reportedly impacted by acid rain.

3.4.6 Soils

A variety of soils typical of the southern New England area are associated with the drainage watersheds which were field inspected. None of the mineral soils located in and around the watershed were mature soils—*spodosols, alfisols, or ultisols.* Only in one place, mentioned earlier, was a tendency toward the formation of a *spodosol* observed. Most of the mineral soils are young and immature and are classified as *entisols*, or *inceptisols.* These soils lack profile differentiation resulting from natural soil-forming processes.

Extensive areas of organic soils *(histosols)* are prevalent in all of the lake watersheds having low pH. The two most prevalent organic soil series are Adrian and Carlisle. The Adrian series contains very poorly drained soils formed in organic material derived from herbaceous plants. These soils are underlain by sand and gravel and are located in depressions and small drainageways of glacial till uplands and outwash plains. The Carlisle soils are similar in all respects, except that they will form into deeper organic horizons often extending down to 140 cm. The Adrian series is strongly acid in the surface horizon, and the Carlisle soil is mildly acid.

3.4.7 Human Use

In contrast to statements made in the Haines report (Haines et al. 1983), most of the watershed areas were being used rather intensely for recreational or residential purposes. It was obvious that these areas were not isolated locations, removed some distance from human use. None of the lakes were without some activity. The dominant type of activity was recreation, followed by residential (largely rural non-farm), agricultural, and even signs of incipient urban. Land cover on most sites was forest; open lands were associated with a few sites used for agricultural purposes.

Various uses are made of recreational sites. Many are private or public camping sites, some are nature centers, and others are fishing lakes. One is a public reservoir with low intensity recreational use. In all cases, people (or at least recent evidence of human use) were encountered, and it was evident that humans have played a significant role in changing the character and dynamics of the watershed in the distant and recent past.

Agricultural use of the watersheds was, in general, of the low-intensity type except for the cranberry region of eastern Massachusetts. No watershed was completely in agricultural use. Most often, a portion (often a minor portion) showed some sign of being used for crop or pasture fields.

3.4.8 Summary and Conclusions

In many ways the southern New England study appeared to be representative of all of the New England area, and in other ways it was atypical. Acidification of lakes was not a major process in most of the lakes inspected. Less than half (6 of 16) of the lakes had pH values less than 5. Acid damage in water, land, or vegetative biota was not readily evident. The data, both from the field and that observed via remote sensing techniques, did not match public perceptions of the destruction attributed to reported acidification processes.

The landscape characteristics, per se, in southern New England were more marginal and transitional than expected from earlier reports. Isolation and primitive and natural conditions were nonexistent. Man's impact on the southern New England area is pervasive. Although the landscape elements are typical of the whole in other areas of New England, intense and direct population pressures on land and water can be witnessed in what are the most inaccessible areas of southern New England. Such situations may not exist in other sections of New England more removed from the large metropolitan centers.

3.5 ADIRONDACK MOUNTAINS TEST SITES

3.5.1 Background

As mentioned in Sect. 2, it has been known for some time that water bodies in the Adirondack Mountains region have had fisheries problems in the form of failures of natural populations and in stocking programs that date back at least to the early 1900s (Smallwood 1918, Kendall 1924, Johnson 1927). More recent investigations (e.g., Schofield 1976) have shown a relationship between lake acidity and the absence of fish life. The acidification of these lakes is generally believed to be caused by acid precipitation. However, Duhaime et al. (1983) have suggested that a number of natural processes associated with anthropogenic activities, but not directly associated with atmospheric acid deposition, are contributing to the acidification of surface waters in this region. This is consistent with the suggestions of Krug and Frink (1983).

It is significant that the Adirondack region, once famous for its production of white pine and spruce, now has but 13% of its area in coniferous forest. Disturbance by man has resulted in the transformation of the Adirondacks into a predominately hardwood area with some conifers mixed in with the hardwoods (Ferree and Davis 1954).

The low volume of wood per acre of Adirondack forest is the result of repeated logging. Most of the forest has been cut at least once, and much of it two or more times (Ferree and Davis 1954). Only about 40,000 hectares of forest in over 2.4 million hectares of the Adirondack Park have not been cut (MacDonald 1925, Ferree and Davis 1954, Thompson 1962). Early lumbering practices, and even most recent lumbering, have been carried out with little or no consideration for maintenance of a high quality forest. Consequently, Adirondack forests are "unhealthy"; most of the wood is diseased or deformed (Ferree and Davis 1954, Thompson 1962).

Several investigators have documented the occurrence of sphagnum in the Adirondack area (Hendry and Vertucci 1980, Singer et al. 1983, Everett et al. 1982). Sphagnum communities are favored by low nutrient environments. Everett et al. (1982) noted that the bedrock of the western Adirondacks has about one-half the calcium content of that of the eastern part. Likewise, the calcium content of western Adirondack soils has been observed to be about one-half that of equivalent soil types of the eastern part (Heimburger 1934). Lakes more acid than pH 5 are concentrated in the western part of the Adirondack Park and the much smaller High Peaks region and appear to be correlated to sandy glacial outwash plains and larger areas of peat, areas that would be expected to contain sphagnum.

An extensive study of three lakes in the western Adirondack Park region has been conducted under the sponsorship of the Electric Power Research Institute (Goldstein and Gherini, 1984). The study area included the watersheds around three lakes: Woods Lake (acidic), Panther Lake (neutral), and Sagamore Lake (in between). The objective of this study is to establish the quantitative nature of the link between surface water acidity and the deposition of atmospheric acids and to derive a theoretical framework for this relationship. The major result of this investigation is a simulation model which calculates the rate of change in the acidity of surface waters as a function of changing atmospheric deposition levels. A major finding is that the acidity of a lake is determined by the interaction of many factors; for example, vegetation, soil, hydrology, geology, limnology, climate, and atmosphere. In addition, it was determined that the routing of water through different flow paths is a major determinant of the alkalinity of a lake and its vulnerability to acidification by atmospheric deposition (Goldstein and Gherini 1984). This study is being extended to include selected watersheds in northwestern Wisconsin, western North Carolina, and the Sierra Nevada Mountains, and a regional study of 20 watersheds in the Adirondacks (Goldstein and Gherini 1984).

Additional data are being collected as part of the National Acid Precipitation Assessment Program. The Adirondack Watershed Data Base will consist of data for 2800 lakes with initial emphasis on 500 headwater lakes. Initial parameters include bedrock class, soil associations, topography, land cover, climate, deposition, disturbance (beavers, fires, logging, cultural structures), wetlands, lake morphometry, lake chemistry, and fish. This data base should be extremely useful when it becomes available.

3.5.2 Preliminary Observations

A procedure similar to that used in southern New England was followed in the remote sensing analysis of the Adirondacks area except that results of the field verification in step 3 (Sect. 3.3.2) were less satisfactory. The MSS data were found to be partially ineffective in identifying key landscape elements due to the coarse resolution of the spectral data (four spectral bands with a pixel size of 80 × 80 meters). Consequently, it was decided to convert to the higher resolution TM data (Fig. A.4) also available from Landsat IV (seven spectral bands with a pixel size of 30 × 30 meters). Steps 1, 2, and 3 (Sect. 3.3.2) were repeated with the TM data. Refinements of these classifications (step 4) are planned, but the results are not available for this interim report.

The research design calls for an eventual quantification of landcover in the drainage basin upstream from each lake selected for study in the Adirondacks and in southern New England. This will be done by defining polygons which approximate basins on the interpreted Landsat images. Measurements will be performed by applying standard functions available on the image processing system. The resulting summary statistics will then be compared to lake characteristics through spatial correlation. Ultimately, it is hoped, this process will be repeated for numerous time periods in order to test both temporal and spatial relationships.

4. CONCLUSIONS

A review of the literature pertinent to landscape and lake acidification relationships, although not clearly establishing a causal relationship between landscape change and lake acidification, does indicate that such a relationship exists and encourages further studies to investigate this relationship.

The observations at Emmons Pond show that changes in the landscape are occurring in the general time frame in which the pond has become more acidic. These observations also indicate that the presence of sphagnum moss in the watershed is contributing to the acidification. These results offer further encouragement to investigate landscape/lake acidification relationships.

The Landsat/ground truth investigations in southern New England, although preliminary, do suggest that satellite imagery can be useful in identifying types of ground cover important to landscape/lake acidification relationships.

Our general conclusion is that there is a landscape and lake acidification relationship and that remote sensing, such as Landsat imagery, can be useful in investigating this relationship. We intend to continue this investigation and extend the studies in the Adirondack region.

5. REFERENCES

Andreas, B. K., and G. E. Host. 1983. "Development of a *Sphagnum* Bog on the Floor of a Sandstone Quarry in Northeastern Ohio," *Ohio J. Sci.*, **8**, 246–253.

Berg, N. 1985. "Acidification of Snowmelt Runoff Water in the Central Sierra Nevada, California," p. 146, in *Abstracts of Papers, 151st National Meeting of the American Association for the Advancement of Science, Los Angeles, Calif., May 26–31, 1985.*

Braekke, F. H. 1981. "Hydrochemistry in low-pH-soils of South Norway 2. Seasonal Variation in Some Peat Land Sites," *Medd. Norsk Inst. Skogf.*, **6**, 12–23.

Charlson, R. J., and H. Rodhe. 1982. "Factors controlling the Acidity of Natural Rainwater," *Nature* **295**, 683–685.

Chittenden, A. K. 1905. "Forest conditions of northern New Hampshire," *U.S.D.A. Bur. For. Bul.* **55**.

Connaughton, C. A. 1935. "The Accumulation and Rate of Melting of Snow as Influenced by Vegetation," J. *Forestry*, **33**, 564–69.

Dahl, K. 1927. "The Effects of Acid Water on Trout Fry," *Salmon and Trout Magazine*, **46**, 35–43.

Defebaugh, J. E. 1906. *History of the Lumber Industry of America*, vol. 1, The American Lumberman, Chicago.

Defebaugh, J. E. 1907. *History of the Lumber Industry of America*, vol. 2, The American Lumberman, Chicago.

Duhaime, P. F., A. G. Everett, and W. C. Retzsch. 1983. *Adirondack Land Use: A Commentary on Past and Present Impacts on Terrestrial and Aquatic Ecosystems*, American Petroleum Institute, Washington, D.C.

Eschner, A. R., and D. R. Satterlund. 1963. *Snow Deposition and Melt Under Different Vegetative Covers in Central New York*, U.S.D.A. For. Serv., Res. Note NE-13.

Eschner, A. R. and D. R. Satterlund. 1966. "Forest Protection and Streamflow from an Adirondack Watershed," *Water Resources Research*, **2**, 765–83.

Everett, A. G. et al. 1982. "Hydrogeochemical Characteristics of Adirondack Waters Influenced by Terrestrial Environments," in *The Second National Symposium on Acid Rain*, October 6–7, 1982, Greater Pittsburgh Chamber of Commerce.

Ferree, M. J., and J. E. Davis. 1954. *Forest Acreage and Timber Volume in the Adirondack and Catskill Regions*, State Univ. of New York, College of Forestry at Syracuse, Bulletin 35.

Ferguson, R. H., and V. S. Jensen. 1963. *The Timber Resources of New Hampshire*, U.S.D.A. For. Serv. Resour. Rept. NE-1.

Ferguson, R. H., and N. P. Kingsley. 1972. *The Timber Resources of Maine*, U.S.D.A. For. Serv. Resour. Bul. NE-26.

Fox, W. F. 1902. *A History of the Lumber Industry in the State of New York,* U.S.D.A. Bur. For. Bul. 34.

Frink, C. R., and G. K. Voigt. 1976. "Potential Effects of Acid Precipitation on Soil in the Humid Temperate Zone," pp. 685-709, in *Proceedings of the First International Symposium on Acid Precipitation and the Forest Ecosystem,* U.S. Dept. of Agriculture Forest Service, General Technical Report NE-23.

Glaser, P. H. 1983. "North American Bogs," *Ecology,* **64,** 1325-26.

Goff, F. G. 1967. "Upland Vegetation," in C. J. Milfred et al., *Soil Resources and Forest Ecology of Menominee County Wisconsin,* Univ. of Wisconsin, Geological and Natural History Survey Bulletin 85.

Goldstein, R. A., and S. A. Gherini [eds.], 1984. *Integrated Lake-Watershed Acidification Study, Summary of Major Results.* Final Report, EPRI-EA-3221, Vol. 4. Electric Power Research Institute Report.

Gorham, E. 1956. "The Ionic Composition of Some Bog and Fen Waters in the English Lake District," *J. Ecol.*, **44,** 142-152.

Gorham, E., and W. H. Pearsall. 1956. "Acidity, Specific Conductivity and Calcium Content of Some Bog and Fen Waters in Northern Britain," *J. Ecol.*, **44,** 129-41.

Haines, T. A., J. Akielaszak, and P. Rago. 1983. *A Regional Survey of the Chemistry of Headwater Lakes and Streams in New England: Vulnerability to Acidification.* Air Poll. and Acid Rain Rept. No. 15, Fish and Wildlife Service, U.S. Dept. of Interior, Washington, D.C.

Harr, R. D., 1981. "Some Characteristics and Consequences of Snowmelt During Rainfall in Western Oregon," *J. Hydrol.*, **53,** 277-304.

Hart, A. C. 1964. "Spruce-Fir Silviculture in Northern New England," pp. 107-10 in *Proceedings of the 1963 Meeting of the Soc. Amer. Foresters Proc.*

Hawley, R. C., and A. F. Hawes. 1912. *Forestry in New England,* John Wiley & Sons, New York.

Heimburger, C. C. 1934. "Forest-Type Studies in the Adirondack Region," Cornell Univ. Agricultural Experiment Station Memoir 165.

Heinselman, M. L. 1963. "Forest Sites, Bog Processes and Peatland Types in the Glacial Lake Agassiz Region, Minnesota," *Ecol. Monogr.*, **33,** 327-74.

Hemond, H. F. 1980. "Biogeochemistry of Thoreau's Bog, Concord, Massachusetts," *Monogr. Ecol.*, **50,** 507-26.

Hendriksen, A. 1979. "A Simple Approach for Identifying and Measuring Acidification of Freshwater," *Nature,* **278,** 542-45.

Hendry, G. R., and F. Vertucci. 1980. "Benthic Plant Communities in Acidic Lake Colden, New York: Sphagnum and the Algae Mat." pp. 314-15, in D. Drablos and A. Tollan [eds.], *Ecological Impact of Acid Precipitation,* SNSF project, Oslo.

Hendry, G. R., C. G. Hoogendyk, and N. F. Gmur. 1983. *Establishing the Acidification Chemistry Information Database (ACID)*, BNL-51707, Brookhaven National Laboratory.

Interagency Task Force on Acid Precipitation. 1983. *National Acid Precipitation Assessment Program, Annual Report 1983 to the President and Congress.*

Jeglum, J. K. 1971. "Plant Indicators of pH and Water Levels in Peatlands at Candle Lake, Saskatchewan," *Can. J. Bot.*, **49**, 1661–76.

Jewell, M. E., and H. W. Brown. 1929. "Studies on Northern Michigan Bog Lakes," *Ecology*, **10**, 427–75.

Johnson, C. E. 1927. "The Beaver in the Adirondacks: Its Economics and Natural History." *Roosevelt Wild Life Bul.*, 4(4), 495–641.

Karlin, E. F., and L. C. Bliss. 1984. "Variation in Substrate Chemistry Along Microtopographical and Water-Chemistry Gradients in Peatlands," *Can. J. Bot.*, **62**, 142–53.

Kendall, W. C. 1924. "The Status of Fish Culture in our Inland Public Waters and the Role of Investigation in the Maintenance of Fish Resources," *Roosevelt Wild Life Bul.*, **2(3)**, 205–351.

Kingsley, N. P. 1977. *The Forest Resources of Vermont*, U.S.D.A. For. Serv. Resour. NE-46.

Krug, E. C., and C. R. Frink. 1983. "Acid Rain on Acid Soil: A New Perspective," *Science*, **221**, 520–25.

Krug, E. C., and P. J. Isaacson. 1984. "Comparison of Water and Dilute Acid Treatment on Organic and Inorganic Chemistry of Leachate from Organic-Rich Horizons of an Acid Forest Soil," *Soil Sci.*, **137(5)**, 370–78.

Krug, E. C., P. J. Isaacson, and C. R. Frink. 1985. "Appraisal of Some Current Hypotheses Describing Acidification of Watersheds," *J. Air Poll. Control Assoc.*, **35**, 109–14.

Kurz, H. 1929. "Influence of Sphagnum and Other Mosses on Bog Reactions," *Ecology*, **9**, 56–69.

Lag, J. 1959. "Influence of Forest Stand and Ground Cover Vegetation on Soil Formation," *Agrochimica*, **4**, 72–77.

Likens, G. E. 1976. "Acid Precipitation," *Chem. & Eng. News*, **54(48)**, 29–44.

Lull, H. W. 1959. "Humus Depth in the Northeast," *J. Forestry*, **57**, 905–909.

Lull, H. W., and F. M. Rushmore. 1960. *Snow Accumulation and Melt Water Under Certain Forest Conditions in the Adirondacks*, U.S.D.A. For. Serv. N.E. For. Exp. Stn. Paper No. 138.

MacConnell, W. P. 1975. *Remote Sensing 20 Years of Change in Massachusetts*, Mass. Agr. Exp. Sta. Bul. 670.

MacDonald, A. 1925. "Policy for Forest Land Acquisition by New York State," *J. Forestry*, **23**, 457–59.

Marbut, C. F. 1951. *Soils: Their Genesis and Classification*, Soil Sci. Soc. Amer., Madison, Wis.

Marshall, R. 1925. "Recreational Limitations to Silviculture in the Adirondacks." *J. Forestry,* **23,** 173–78.

Mason, J., and H. M. Seip. 1985. "The Current State of Knowledge on Acidification of Surface Waters and Guidelines for Further Research," *Ambio,* **14(1),** 45–51.

Mueller, A. J. 1974. *Twenty Years of Change in Open Freshwater Wetlands on the Massachusetts Coastal Plain,* M.Sc. Thesis, University of Massachusetts.

National Research Council. 1981. *Atmosphere-Biosphere Interactions: Toward a Better Understanding of the Ecological Consequences of Fossil Fuel Combustion,* National Academy of Sciences, Washington, D.C.

New York State Department of Environmental Conservation. 1982. *Proceedings of the Acid Precipitation Research Needs Conference,* State University of New York, Syracuse.

Noggle, J. C. et al. 1984. "Investigations of the Role of Internally Generated Hydrogen Ions and Aluminum Ions on Surface Water Acidification," Paper 84-22.3, 77th Annual Meeting of the Air Pollution Control Association.

Patrick, R., V. P. Binetti, and S. G. Halterman. 1981. "Acid Lakes from Natural and Anthropogenic Causes," *Science,* **211,** 446–48.

Pfeiffer, M. H., and P. J. Festa. 1980. *Acidity Status of Lakes in the Adirondack Region of New York in Relation to Fish Resources,* N.Y. Dept. of Environmental Conservation.

Powell, D. S., and T. J. Considine. 1982. *An Analysis of Pennsylvania's Forest Resources,* U.S.D.A. For. Serv. N.E. For. Exp. Stn. Res. Bul. NE-69.

Quinn, F. H. 1981. "Secular Changes in Annual and Seasonal Great Lakes Precipitation, 1854-1979, and Their Implications for Great Lakes Water Resource Studies," *Water Resources Research,* **17,** 1619–24.

Retzsch, W. C., A. G. Everett, P. F. Duhaime, and R. Northwanger. 1982. *Alternative Explanations for Aquatic Ecosystems Effects Attributed to Acidic Deposition,* Everett and Associates, Rockville, Maryland.

Rigg, G. B. 1940. "The Development of Sphagnum Bogs in North America," *Bot. Rev.,* **6,** 666–93.

Rosenqvist, I. T. 1978. "Alternative Sources for Acidification of River Water in Norway," *Sci. Total Environment,* **10,** 39–49.

Satterlund, D. R., and A. R. Eschner. 1965. "Land Use, Snow, and Streamflow Regimen in Central New York," *Water Resourc. Res.,* **1,** 397–405.

Schneider, W. J., and G. R. Ayer. 1961. *Effect of Reforestation on Streamflow in Central New York,* U.S.G.S. Water-Supply Paper 1602.

Schofield, C. L. 1976. "Acid Precipitation: Effects on Fish," *Ambio,* **5,** 228–30.

Schwitzer, C. R. 1978. "Vegetation and Nutrient Status of Northern Michigan Fens." *Can. J. Bot.,* **56,** 3044–51.

Seip, H. M. 1980. "Acidification of Freshwater—Sources and Mechanisms," pp. 358–366, in D. Drablos and A. Tollan [eds.], *Ecological Impact of Acid Precipitation*, SNSF Project, Oslo.

Shaler, N. W. 1890. "General Account of the Fresh-Water Morasses of the United States with a Description of the Dismal Swamp District," *10th Annual Report U.S.G.S.*, 261–312.

Sims, R. A., D. W. Cowell, and G. M. Wickware. 1982. "Classification of Fens Near Southern James Bay, Ontario, Using Vegetational Physiognomy," *Can. J. Bot.*, **60**, 2608–23.

Singer, R., D. A. Roberts, and C. W. Boylen. 1983. "The Macrophytic Community of an Acidic Lake in Adirondack (New York, U.S.A.): A New Depth Record for Aquatic Angiosperms," *Aquatic Botany*, **16**, 44–57.

Sjors, H. 1950. "On the Relation Between Vegetation and Electrolytes in Northern Swedish Mire Waters," *Oikos*, **2**, 241–58.

Skartveit, A. 1981. "Relationships Between Precipitation Chemistry, Hydrology, and Runoff Acidity," *Nordic Hydrology*, **12**, 65.

Smallwood, W. M. 1918. "An Examination of the Policy of Restocking the Inland Waters with Fish." *American Naturalist*, **52**, 322–52.

Swan, J. M. A. and A. M. Gill. 1970. "The Origin, Spread, and Consolidation of a Floating Bog in Harvard Pond, Petersham, Massachusetts," *Ecology*, **51**, 829–40.

Tamm, O. 1950. *Northern Coniferous Forest Soils*, Scrivener Press, Oxford.

Thompson, R. C. 1962. "The Doctrine of Wilderness: A Study of the Policy and Politics of the Adirondack Preserve-Park," Ph.D. Thesis, College of Forestry, Syracuse University.

Tiurin, I.V., V. A. Burenkov, and A. S. Masslov. 1935. "Contribution to the Study of the Swamping Process of Forest Podzols Soils After Cutting," *Trans. 3rd Intern. Cong. Soil Sci.*, **1**, 379–81.

Troedsson, T. 1980. "Long-Term Changes of Forest Soils," *Ann. Agr. Fenn.*, **19**, 81–84.

Ugolini, F. C., and D. H. Mann. 1979. "Biopedological Origin of Peatlands in Southeast Alaska," *Nature*, **281**, 366–68.

U.S. Department of Energy. 1983. *Acid Rain Information Book*, Second Edition, DOE/EP-0018/1.

U.S. Forest Service. 1982. *An Analysis of the Timber Situation of the United States 1952–2030*, For. Serv. Rept. No. 23.

Verry, E.S. 1975. "Streamflow Chemistry and Nutrient Yields from Upland-Peatland Watersheds in Minnesota," *Ecology*, **56**, 1149–57.

Viro, P. J. 1974. "Effects of Forest Fire on Soil," pp. 7–45 in T. T. Kozlowski and C. E. Ahlgren [ed.], *Fire and Ecosystems*, Academic Press, New York.

Wiklander, L. 1975. "The Role of Neutral Salts in the Ion Exchange Between Acid Precipitation and Soil," *Geoderma*, **14**, 93–105.

Wiklander, L. 1973/74. "The Acidification of Soil by Acid Precipitation," *Grundforbattring*, 26, 155-64.

Williams, B. L., J. M. Cooper, and D. G. Pyatt. 1978. "Effects of Afforestation with *pinus contorta* on Nutrient Content, Acidity and Exchangeable Cations in Peat," *Forestry*, **51**, 29–35.

APPENDIX A

ORNL-PHOTO 4814-85

Fig. A.1. 1934 aerial photograph of Emmons Pond. Previously abandoned agricultural land away from major roads is seen as patterned land beneath the young forest.

ORNL-PHOTO 4815-85

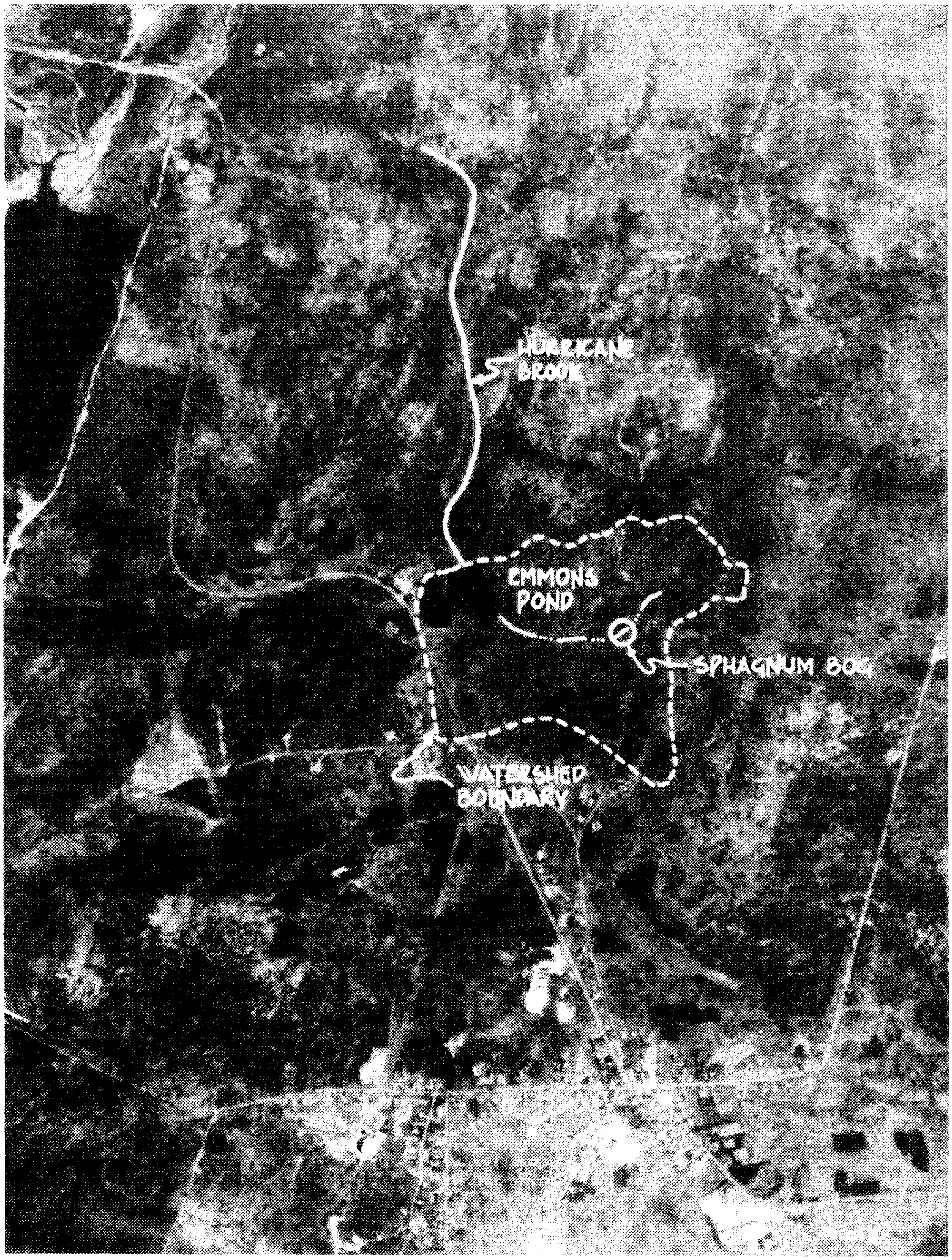

Fig. A.2. 1980 aerial photograph of Emmons Pond. Much of the abandoned agricultural land has reverted to forest.

ORNL-PHOTO 4942-85

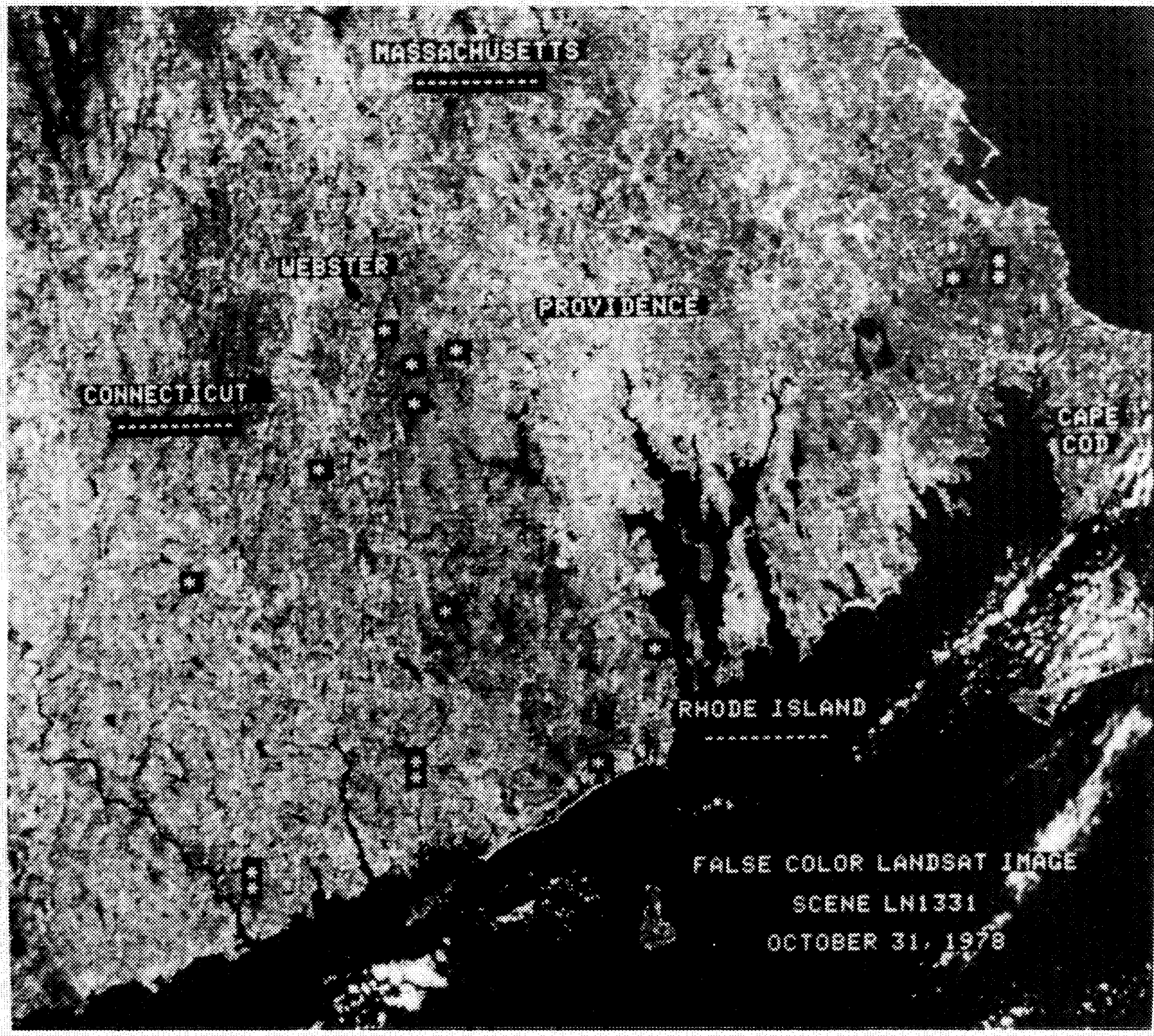

Fig. A.3. Multispectral scanner scene of southern New England showing ponds investigated.

ORNL-PHOTO 4943-85

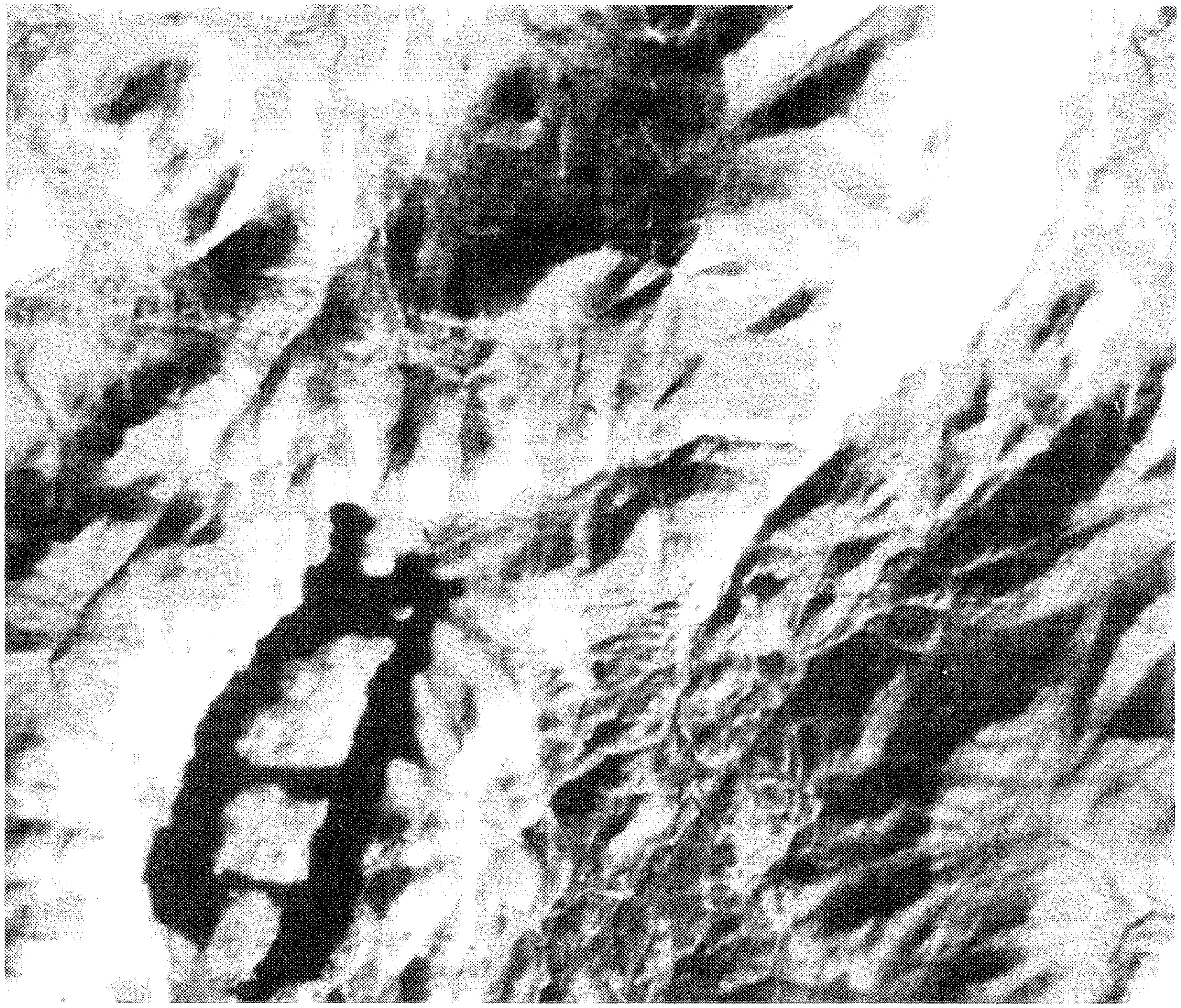

Fig. A.4. Thematic mapper scene around Lake Placid.

INTERNAL DISTRIBUTION

1–5. F. P. Baxter
6. J. B. Cannon
7. S. W. Christensen
8. J. E. Christian
9. N. S. Dailey
10–14. J. E. Dobson
15. R. C. Durfee
16. W. Fulkerson
17. E. L. Hillsman
18–22. R. B. Honea
23. M. T. Huie
24. C. T. Hunsaker
25. M. R. Ives
26. D. W. Jones
27. J. O. Kolb
28. R. S. Loffman
29. R. Lee
30. F. C. Maienschein
31. L. N. McCold
32. R. J. Olson
33. R. D. Perlack
34. A. M. Perry
35. C. H. Petrich
36–40. R. M. Rush
41. D. S. Shriner
42. F. Southworth
43. R. A. Stevens
44. R. S. Turner
45. W. VanWinkle
46. D. Vogt
47. Central Research Library
48. Environmental Sciences Library
49–50. Laboratory Records
51. Laboratory Records—RC
52. ORNL Patent Office

EXTERNAL DISTRIBUTION

53. Office of Assistant Manager for Energy Research and Development, DOE-ORO, P.O. Box E, Oak Ridge, TN 37831
54. K. B. Adams, Center for Earth and Environmental Science, State University of New York at Plattsburg, Plattsburg, NY 12901
55. Kurt D. Anderson, New York Power Pool, 3890 Carman Road, Schenectady, NY 12065
56. Richard H. Ball, Acid Deposition Assessment Staff, Environmental Protection Agency, 401 M Street SW, RD-676, Washingtin, DC 20460
57. David A. Bennett, Acid Deposition Assessment Staff, Environmental Protection Agency, 401 M Street SW, RD-676, Washington, DC 20460
58. Neil H. Berg, Pacific Southwest Forest and Range Experiment Station, 1960 Addison Street, P.O. Box 245, Berkeley, CA 94701
59. Robert W. Brocksen, Wyoming Water Research Center, P.O. Box 3067, University Station, Laramie, WY 82071
60. Douglas Carter, Regional Assessment Division, Department of Energy, MS F2-13, Rm 4G-057, Forrestal Building, 1000 Independence Avenue, Washington, DC 20585
61. J. R. Colquhoun, Fisheries Division, New York State Department of Environmental Conservation, 50 Wolf Road, Albany, NY 12233
62. R. P. Curran, Adirondack Park Agency, P.O. Box 99, Ray Brook, NY 12977

63. A. G. Everett, Everett and Associates, 416 Hungerford Drive, Rockville, MD 20850
64. S. Malcolm Gillis, Professor of Economics and Public Policy, Department of Economics, Duke University, Durham, NC 27706
65. Robert A. Goldstein, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303
66. Ely Gonick, Senior Vice President, Technology, International Paper Co., 77 West 45th Street, New York, NY 10036
67. James Gutensohn, Commissioner, Department of Environmental Management, 100 Cambridge Street, Boston, MA 02202
68. Charles Hakkarinen, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303
69. Ted Harris, Deputy Director, Regional Assessment Division, Department of Energy, Mail Stop E-201, Washington, DC 20545
70. C. R. Horn, Environmental Protection Agency, 401 M Street SW, Washington, DC 20460
71. Peter House, National Science Foundation, 1800 G Street NW, Washington, DC 20550
72. H. C. Jones, Air Quality Branch, Tennessee Valley Authority, Muscle Shoals, AL 35660
73. Boris Kachura, Program Director, Engineering Environment and National Resources, PEMD/GAD, 44 G Street NW, Washington, DC 21504
74. Fritz R. Kalhammer, Vice President, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303
75. Roger E. Kasperson, Professor of Government and Geography, Graduate School of Geography, Clark University, Worcester, MA 01610
76. W. A. Kretser, New York State Department of Environmental Conservation, Route 73, Ray Brook, NY 12977

77–81. Edward C. Krug, Atmospheric Chemistry Section, Illinois State Water Survey, 2204 Griffith Drive, Champaign, IL 61820

82. Martin Lessen, Consulting Engineer, 12 Country Club Drive, Rochester, NY 14618
83. Donald Mader, Department of Forestry and Wildlife Management, University of Massachusetts, Amherst, MA 01003
84. John L. Malanchuk, Acid Deposition Assessment Staff, Environmental Protection Agency, 401 M Street SW, RD-676, Washington, DC 20460
85. René Malès, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303
86. Jack S. Mattice, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303
87. Michael M. McCarthy, School of Environmental Planning, University of Melbourne, Parkville, Victoria, Australia 3052
88. William McFee, Agronomy Department, Purdue University, West Lafayette, IN 47907

89–93. Robert W. Peplies, Department of Geography, East Tennessee State University, Johnson City, TN 37601

94. Ralph M. Perhac, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303
95. Charles W. Philpot, Forest Service, Department of Agriculture, Room 606, RPE, P.O. Box 2417, 12th and Independence Avenue SW, Washington, DC 20013
96. Daniel D. Richter, School of Natural Resources, Dana Hall, University of Michigan, Ann Arbor, MI 48109
97. I. Th. Rosenqvist, Institute of Geology, University of Oslo, Oslo, Norway
98. George Schier, Forest Service, 359 Main Road, Deleware, OH 43105
99. Jerald L. Schnoor, Civil and Environmental Engineering, University of Iowa, Iowa City, IA 52242
100. William H. Smith, School of Forestry and Environmental Study, Yale University, New Haven, CT 06511
101. M. Ali Tabatabai, Department of Agronomy, Iowa State University, Ames, IA 50011
102. Gary Tannahill, Exxon Corporation, P.O. Box 2180, Houston, TX 77001
103. Peter L. M. Veneman, 12A Stockbridge Hall, University of Massachusetts, Amherst, MA 01003
104. Walter L. Warnick, Program Integration Analysis Division, Office of Energy Research, Department of Energy, ER-32, G-226, Washington, DC 20545

105–114. Ted Williams, Office of Environmental Analyses, Department of Energy, Room 4G-036, Forrestal Building, 1000 Independence Avenue SW, Washington, DC 20585

115–141. Technical Information Center, Department of Energy, P.O. Box 62, Oak Ridge, TN 37831