THE SCIENTIFIC CAREER OF EVILLE GORHAM*

Professor Gorham's researches over the past 65 years have spanned an unusual range of subjects, including among others such topics as acid rain, air pollution and human health, radioactive fallout, the ecology and biogeochemistry of northern peatlands, fossil pigments in lake sediments, physical limnology, forest litter production, the development of forest humus layers, salmon embryology, weight/density relationships in plants and the history of ecology and biogeochemistry. The following pages detail the major aspects of his research career.

ATMOSPHERIC INPUTS TO NATURAL ECOSYSTEMS

From the 1950's through the 1970's Gorham pioneered the study of atmospheric inputs of both nutrients and toxins to natural ecosystems in his research on the chemistry of rain and snow in the English Lake District (15, 33) and in later studies in Canada and the USA. Such studies have been of vital importance to learning how ecosystems function and how they respond to air pollution, as exemplified by the long-term investigations of terrestrial ecosystems by Gene Likens and his colleagues in the Hubbard Brook Experimental Forest of New Hampshire and of aquatic ecosystems by David Schindler and his colleagues in the Experimental Lakes Area of NW Ontario. Atmospheric inputs are of critical importance in developing chemical budgets of inputs to, outputs from, and storages in ecosystems, both for nutrient elements such as nitrogen, calcium and potassium, and for toxins such as acids, heavy metals and organic micro-pollutants. Gorham's early work was the first to demonstrate the importance of such atmospheric inputs of chemical elements to lakes and to bogs, and his widely cited review in 1961 (53) provided a strong stimulus to further research on the topic. His interest in the topic continued in the United States in the 1970's and 1980's, and led to a consideration of how the chemical budgets of ecosystems are likely to change over time, resulting in another oft-quoted review (96).

ACID RAIN

Gorham's studies of atmospheric deposition in the mid-1950's led him to the discovery that acid precipitation was falling in the rural English Lake District, far from sources of urban air pollution (15). Rain chemistry in the area was dominated by sodium chloride from sea salt when the winds blew from the Irish Sea, whereas it was dominated by sulfuric acid from the oxidation of sulfur

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dioxide when the winds blew from the urban-industrial areas of northern Britain where large amounts of coal were burned. Surprisingly, Lake District rain was generally more acid than rain in British cities, where local deposition of alkaline fly ash from chimneys and soil dust fall provided substantial neutralizing capacity. At the same time Gorham used studies by his colleague John Mackereth, of surface-water chemistry in the Lake District, to demonstrate that atmospheric deposition dominated the composition of dilute waters in mountain ponds and lakes on hard, poorly weathered rocks, and acidified them. In marked contrast, the waters of lakes on softer, more easily weathered rocks were not acidified (15, 33).

These studies in England were followed by research with Alan Gordon on lakes and ponds around the metal smelters at Sudbury and Wawa in Ontario. Close to the smelters, sulfides oxidized by the smelting process acidified surface waters very severely (to pH 3.2), with the effect declining steadily away from them (50, 59). These examples demonstrated indisputable point-source origins for acid rain. With increasing acidity the species diversity of aquatic vascular plants declined sharply, although it was indicated that pollution by copper and nickel might also be involved (58). These aquatic studies were complemented by research on the effect of plumes of gaseous sulfur dioxide emanating from the Wawa smelter upon the vascular-plant communities of upland soils. It revealed that within 10 miles of the smelter there occurred a sharp decline in species diversity, with only two species (out of 20-40 observed in unpolluted forests) surviving close to the smelter smokestack (59). The pollution effect there took the form of a successive "peeling away" of tree, shrub, and ground flora layers as the severity of sulfur-dioxide fumigation increased. (This turned out to be an effect very similar to that caused experimentally by gamma radiation, observed later by George Woodwell at a Brookhaven forest exposed to radiation from cobalt-60). At both Sudbury and Wawa the plant species most sensitive to pollution was white pine, the most valuable economic species of the forests there.

These Canadian studies were followed by studies at three sites across northern Minnesota with Steven Eisenreich and several graduate students. They revealed a strong contrast in the effects on rain and snow chemistry (including both major ions and trace metals) of acid pollution inputs from the east and neutralizing inputs of calcareous dust-fall from the soils of the western prairies (103). After that, Gorham and other colleagues analyzed the interrelationships of ions in atmospheric deposition east of the Mississippi to develop a limit for deposition of wet sulfate that would protect lakes and streams sensitive to acid deposition (119). With yet another group of colleagues he described the threat to peatlands from acid deposition (116, 129).

EFFECTS OF AIR POLLUTANTS UPON HUMAN HEALTH

His studies of acid rain led Gorham to an interest in the possible effects of urban air pollution on respiratory diseases in British. cities. Employing mortality statistics from the Registrar-General's annual statistical reviews for 1950-54, he sought correlations with a variety of pollutants for which data on atmospheric deposition had been collected by the U.K. Department of Scientific and Industrial Research. It turned out that mortality rates for three different respiratory diseases -- lung cancer, bronchitis, and pneumonia -- correlated with different pollutants. As expected, rates for lung cancer correlated with deposition of tar (44). Bronchitis mortality correlated with the pH of atmospheric precipitation (39), which in British cities is primarily due to hydrochloric acid because of the high chlorine content of many British coals (38) and the fact that much of the sulfur dioxide emitted there travels far from its points of origin. Pneumonia mortality correlated not with pH but with the deposition of sulfate (46), an observation of interest because fine particulates in the atmosphere are often dominated by acid sulfates.

RADIOACTIVE FALLOUT

The 1957 fire at the Windscale plutonium facility in the English Lake District impelled Gorham to investigate the accumulation of radioactive fallout by plants in the area (37, 43). As it turned out, fallout from the testing of nuclear weapons turned out to be far more important, and he discovered, for the first time, the extraordinary capacity of mosses and lichens -- largely dependent for their mineral supply upon atmospheric deposition -- to concentrate radioisotopes in their tissues. He noted further that unusually high levels of strontium-90 observed by other investigators in the bones of Norwegian reindeer, for which lichens are an important component of the diet, testified to the possibility of strong bioaccumulation in northern food chains. This observation foreshadowed later work by others in Alaska and Finland on the high levels of fallout uptake by Alaskan Inuit and Lapland Sami living on such food chains.

PEATLAND ECOLOGY AND BIOGEOCHEMISTRY

Gorham’ s work on peatlands also began in the English Lake District, where he investigated the acidification of these ecosystems. Acidification occurred when peat accumulated sufficiently to isolate the surface waters and peats from inputs of bases from adjacent mineral soils (10). He later, with various colleagues, contrasted such natural processes of acidification with those caused by acid deposition (116, 129), and established that complex colored organic acids, produced by the decomposition of plants and exported naturally from peat bogs, are an important factor causing lake acidification in the boreal zone (126, 161). He also observed that peatlands can mitigate acid deposition in catchments where they are present, because of microbial reduction of sulfate in their anaerobic peats (120). This affects only the acid deposition falling on the peatland, and is active chiefly in summer (161), so that the effects of colored organic acids from bogs and acid deposition are, in part, additive (126).

With his Research Associate Dr. Jan Janssens, Gorham has used fossil moss assemblages in dated cores of peat to calculate (by transfer functions representing pH and water-table tolerances of modern moss assemblages) depth profiles of peatland pH and water-table levels over thousands of years (147). This paleoecological technique has established background levels against which to assess the human influence upon peatlands of both acid deposition and climatic warming, which is likely to lower water tables in many peatlands. It also revealed that acidity in peatlands can develop rapidly once peat accumulation is sufficient to isolate the surface from inputs of bases from surrounding mineral soils or upwelling groundwater. Sites that have been circum-neutral sedge fens for thousands of years can, in this way, shift to strongly acid *Sphagnum* bogs within decades to a couple of centuries, and then remain acid for further millennia (147). This is in marked contrast to the case of upland forest soils, which acidify only gradually in response to the leaching of soil bases by percolating rainfall. The fen waters are buffered around neutrality, pH 7, primarily by calcium bicarbonate from soil weathering, whereas the bog waters are buffered around pH 4 by complex, colored humic acids produced by organic decomposition. The point at which fen waters become liable to rapid acidification — whether naturally or by acid rain -- is marked by very low alkalinity and a pH of about 6.0 (116).

Another recent interest has been the role of peatlands in the global carbon cycle, because of their tendency to sequester very large amounts of carbon (~ 400 billion tons) as peat and their importance in emitting methane -- the second most important greenhouse gas -- to the atmosphere (141, 149). In this connection Gorham has pointed out the potential for substantial biotic feedbacks to the carbon cycle from global warming, which is likely to lower water tables in the peatlands of the southern boreal zone. If the frequency of droughts and fires increases sufficiently for subterranean peat fires to smolder for years in the remote peatlands of Canada and Russia, large amounts of carbon dioxide could be emitted to the atmosphere, probably accompanied also by emissions of methane because of incomplete combustion of still-moist peat (149, 154). In contrast, in the northern boreal zone warming is likely to melt the permafrost underlying many plateau bogs. These are relatively inactive in the carbon cycle, but if flooded are likely to be transformed into sedge fens that will actively sequester carbon dioxide from the atmosphere but also release large amounts of methane. How all these possibilities might play out in the extensive northern peatlands of the boreal and subarctic zones under global-warming scenarios warrants a major program of investigation.

In recent years Gorham and several colleagues have investigated the pattern and process of peatland initiation in North America following the retreat of the Laurentide ice sheet over the past 20,000 years (171). Initiation generally lagged 4,000 years behind deglaciation, peaked between 7,000 and 8,000 years ago, and is projected to continue for millennia. A recent investigation (172) examined the long-term sequestration of 163 Pg of carbon in these peatlands. Very precise modeling suggests – ignoring possible effects of global warming – that this amount could double over the next 20,000 years, and that carbon sequestration in peatlands has been important in global carbon dynamics during the Holocene.

FOSSIL PIGMENTS IN LAKE SEDIMENTS

Throughout the 1960s to the mid-1970's Gorham produced, in the latter period with his student Jon Sanger, a series of papers on fossil plant pigments -- chlorophyll derivatives and carotenoids -- in lake sediments. These were investigated as indices to lake productivity (47, 82), as guides to lake evolution (54), and as a way of determining the primary sources (the lakes themselves or their drainage basins) of sedimentary organic matter (84). Finally, in 1976, they were employed as a tool to determine stratigraphically in sediment cores the timing of onset and the progress of cultural eutrophication in lakes (88).

MISCELLANEOUS INVESTIGATIONS

Gorham's M.Sc. thesis dealt experimentally with the influence of temperature on development in salmon embryos (6). He was able to show that, within the normal range of temperature for development, the sequence of events (e.g., eye pigmentation, appearance of blood vessels in the yolk sac) could be altered by subjecting salmon eggs to lower or higher temperatures. This suggested an explanation for a variety of major abnormalities (e.g., two heads, no jaws, hump-back) that were observed as the result of growth at temperatures beyond the normal limits for survival; thermal dislocation of the processes of embryonic differentiation had finally reached a point at which normal development could no longer proceed. The environmental significance of these results became apparent later in the observation by other scientists that embryos are often unusually susceptible to thermal pollution.

Gorham's Ph.D. thesis dealt with the acidification of surface soils in both woodlands and wetlands of the Lake District as they became steadily more organic (7, 10). This set the stage for his long interest in ecosystem acidification, which has continued to the present day.

A brief focus in the mid-1960's was on litter production in forests. This came about because at the time a great interest was beginning to develop in the net primary productivity of natural ecosystems. Data were few, but Gorham observed that many data were available worldwide on forest litter-fall, a major component of annual forest productivity. With his colleague Roger Bray he compiled a global data base from which it became apparent that temperature was the major controlling factor, with litter-fall (as dry weight) ranging from about 1 ton per hectare in arctic and alpine stands to 11 tons per hectare in equatorial forests (63). Many other aspects of litter-fall were also treated in this first systematic review of the topic, which consequently became widely cited.

Another frequently cited paper concerned the relationship of shoot weight to shoot density in closed stands of a range of species from tall trees to plants as small as a moss. This study revealed that a simple relationship, $w = 9700d^{-3/2}$ (w = shoot dry weight in grams, d = shoot density per square meter), applied over five orders of density and eight orders of shoot weight (95). This meant that in such stands above-ground biomass could be estimated approximately from shoot density; it ranged from about 26 kilograms per square meter for tall trees to as little as 0.1 kilograms per square meter for a large moss.

Other studies dealt with physical limnology (32, 64, 137), effects of smelter pollution upon forests and lakes (58, 58, 59), chemical classification of lakes (86, 111), penetration of bog peats and lake sediments by tritium in radioactive fallout (74), distribution of photosynthetic bacteria in relation to sediment pH and redox potential (80), floristic aspects of delimiting the prairie/forest border (144), the value of paleoecology in monitoring ecosystems (167), and the history of ecology and biogeochemistry (9, 87, 102, 136, 142, 145).

Recently Gorham described his "opportunistic" approach to studies of ecology and biogeochemistry (173), relying on serendipity and Pasteur's celebrated dictum: "Chance favors the prepared mind".

EDUCATIONAL ACTIVITIES

Professor Gorham has been active in both university and public education. He has taught a variety of university courses, and devised -- with colleagues -- three designed to educate students about environmental problems: in the 1970's a course for non-scientists entitled "Biology and the Future of Man," in the 1980's one for senior and graduate students in science entitled "Ecological Assessment of Environmental Pollution," and in the 1990's another course for non-scientists entitled "Our Changing Planet." He has also given seminars at many colleges and universities, as well as a variety of research groups and workshops both in North America and abroad. Hundreds of talks on environmental topics -- many on radio and television -- have been given to citizen groups and to public and private agencies. He also served for several years on the Board of The Acid Rain Foundation, an organization devoted to educating school children, and has been an advisor to its successor (and broader) educational organizations Sci-Link and Globe-Net.

PROFESSIONAL SERVICE

Gorham has served a variety of professional societies in diverse roles, including membership in several environmentally-related committees of the U.S. National Research Council and several panels and workshops of the Royal Society of Canada. In 1978 he was one of four scientists (the others were Ellis Cowling, James Galloway and William McPhee) who produced for the President's Council on Environmental Quality a report recommending research needed in the field of atmospheric precipitation and its ecological effects. That report provided a draft plan for the National Acid Precipitation Assessment Program, and laid the foundation for its mandate in President Carter's Second

Environmental Message in 1979 and its legislative mandate as Public Law 96-294.

PUBLIC SERVICE

Gorham has testified at many hearings on environmental matters at various levels, for instance local (Minneapolis Park Board), state (House Agriculture Committee), and federal (Subcommittee on Oversight and Investigations, House Committee on Interstate and Foreign Commerce). He has also been a member of many public bodies concerned with environmental problems, for instance the Peatland Protection Area Review Committee of the Minnesota Department of Natural Resources and the Health and Environmental Research Advisory Committee of the U.S. Department of Energy. He was also (*inter alia*) a member of the Water Science and Technology Board of the National Research Council, and of the Council of Scientific Advisors to the Marine Biological Laboratory, Woods Hole, Massachusetts.

CONCLUSION

As seen above, Professor Gorham's career has demonstrated more than half a century of commitment to the study of a variety of environmental problems. He has seen these both as problems in fundamental science and as problems of concern to students, legislators and citizens, all of whom he has attempted to educate on such matters.

A SUMMARY OF EVILLE GORHAM'S SCIENTIFIC CAREER

Eville Gorham's 65 years of research have focused chiefly on two interrelated, unifying themes: the ecological and biogeochemical importance of atmospheric deposition of diverse materials to infertile and unproductive lakes, peatlands and forests, and the acidification of such ecosystems both naturally and owing to air pollution caused by fossil-fuel combustion. In several pioneering studies from 1955 to 1963 he described the spread of "acid rain" into rural areas from its urban/industrial sources and its role in lake acidification. Included in these studies was the effect of sulfur dioxide pollution from metal smelters at Sudbury and Wawa, Ontario, upon forest vegetation, soils and lakes. More recently, in 1984 Gorham examined the ecological effects of acid deposition upon peatlands and in the same year calculated the maximum rate of loading for wet-sulfate deposition in the eastern USA that, if not exceeded, would protect sensitive lakes and streams. Natural acidification of lakes by colored organic acids from peat bogs — very common in the boreal zone — was demonstrated conclusively in

1986, when he showed that both it and acid deposition were responsible for acidifying lakes around the urban center of Halifax, Nova Scotia. In the words of Ellis Cowling: “In a long series of papers beginning in 1955, Gorham. . . built the major foundations for our present understanding of the causes of acid precipitation and its impact on aquatic ecosystems” (Environmental Science and Technology 16, 112A, 1982).

In the late 1950’s Gorham investigated the relationships between respiratory diseases and atmospheric deposition in British cities. His studies revealed that mortality from lung cancer was related to tar deposition and bronchitis mortality to the acidity of precipitation, which was chiefly due to hydrochloric acid in these urban areas. Pneumonia mortality was related to the deposition of sulfates in urban areas, and not to acidity.

In 1958 Gorham discovered the extreme ability of mosses and lichens to concentrate radioactive fallout, and in a later paper indicated its strong potential thereby to contaminate northern food chains.

Gorham has long been an internationally recognized leader in the study of northern peatlands, ecosystems that cover 12% of Canada and comparably large areas in Russia and Fennoscandia. His special interests have been their acidification, and their role in the cycle of carbon. From 1980 to 1985 he organized and led a major, NSF-funded project on the ecology and biogeochemistry of *Sphagnum* (moss) bogs across North America that involved 13 co-investigators at five institutions and produced well over 100 papers. A widely cited 1991 article dealt not only with the important role of northern peatlands in the global carbon cycle, but also their likely responses to global warming. Recent studies concerned the initiation of peatlands in North America following the Laurentide deglaciation and projected into the future, and the long-term sequestration of atmospheric carbon in them.

During the 1960s and 1970’s Gorham published an innovative series of papers on the role of fossilized plant pigments in lake sediments as indicators of lake productivity and evolution, and the balance between inputs to sedimentary organic matter from within lakes and from their drainage basins. The series culminated in a 1976 paper on pigments in a core of lake sediment that demonstrated their paleoecological usefulness in establishing the onset of cultural eutrophication.

In 1979 Gorham published a widely cited paper on biomass/density relationships in pure stands of plants in natural habitats that set upper limits for above-ground standing crop at varying stem densities. Other papers covered such diverse topics as salmon embryology, forest litter production, the development of woodland humus layers, floristic boundaries, physical limnology, and factors influencing the distribution of purple photosynthetic bacteria. In addition he has published several papers on the history of science, including in

1991 a major contribution concerning the origins and development of biogeochemistiy.

Gorham has collaborated in devising new courses in environmental science for both scientists and non-scientists, and has given hundreds of talks on environmental problem -- many on radio and TV -- to the general public. He has also been active in service to his professional societies, including the National Academy of Sciences and the Royal Society of Canada, and to governmental and private agencies and organizations concerned with environmental problems here and abroad.

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