Whole-ecosystem nitrogen effects research in Europe

ARTICLE *in* ENVIRONMENTAL SCIENCE AND TECHNOLOGY · AUGUST 1993

Impact Factor: 5.33 · DOI: 10.1021/es00045a002

1 AUTHOR:

Timothy Sullivan
E&S Environmental Chemistry, Inc.

Whole-Ecosystem Nitrogen Effects Research in Europe

TIMOTHY J. SULLIVAN
E&S Environmental Chemistry, Inc.
Corvallis, OR 97339

Concern was raised in the mid-1980s about the possible adverse effects on soils, forests, and drainage waters from atmospheric deposition of inorganic nitrogen compounds. Although some high-quality research is being conducted in the United States on the environmental effects of atmospheric nitrogen deposition (*1, 2*), such research is being conducted to a far greater extent in Europe. The number of comprehensive and integrated European nitrogen studies has increased tremendously, especially in the past three years (Figure 1).

This research is important for the United States because, whereas sulfur emissions have been declining since the 1970s throughout the eastern United States, atmospheric nitrogen emissions have merely leveled off (*3*). Furthermore, ecosystem-level investigations of nitrogen effects in Europe are beginning to yield additional benefits in other fields of environmental research, particularly those related to climatic effects.

European forests are apparently becoming nitrogen saturated. In addition, there is concern that the climate of northern Europe is growing warmer. Such a warming trend may have important implications for nitrogen cycling in European forests because nitrogen mineralization and nitrification can be enhanced by warm soil temperatures and episodic drying events, especially where soil organic nitrogen pools are large.

Nitrogen deposition increases the emissions of N_2O from forest soils (*4*) and may decrease CH_4 uptake (*5*). Both increased N_2O production and decreased CH_4 consumption would increase the concentration of greenhouse gases in the atmosphere. Thus there are important linkages between nitrogen deposition (and consequent ecosystem effects) and the release of greenhouse gases that have been implicated in potential global climate change.

Although the current level of scientific understanding of nitrogen cycling in forested ecosystems is far from complete, important strides rapidly are being made. The results of the broad array of manipulation and process-level studies under way in international research networks will provide critical information to improve our knowledge about this complex topic.

International networks

European scientists have approached questions related to nitrogen dynamics by forming large multidisciplinary, multi-investigator research teams. This approach is practical because of the complexities of the nitrogen cycle; the number of scientific disciplines involved in its study; and the emergence of expensive, large-scale, whole-system manipulation as a tool for studying nitrogen effects. A high degree of international and interinstitutional cooperation has developed in recent years in Europe. This spirit of cooperation is evident in several ongoing international umbrella projects on nitrogen effects, especially NITREX, EXMAN, and ENCORE.

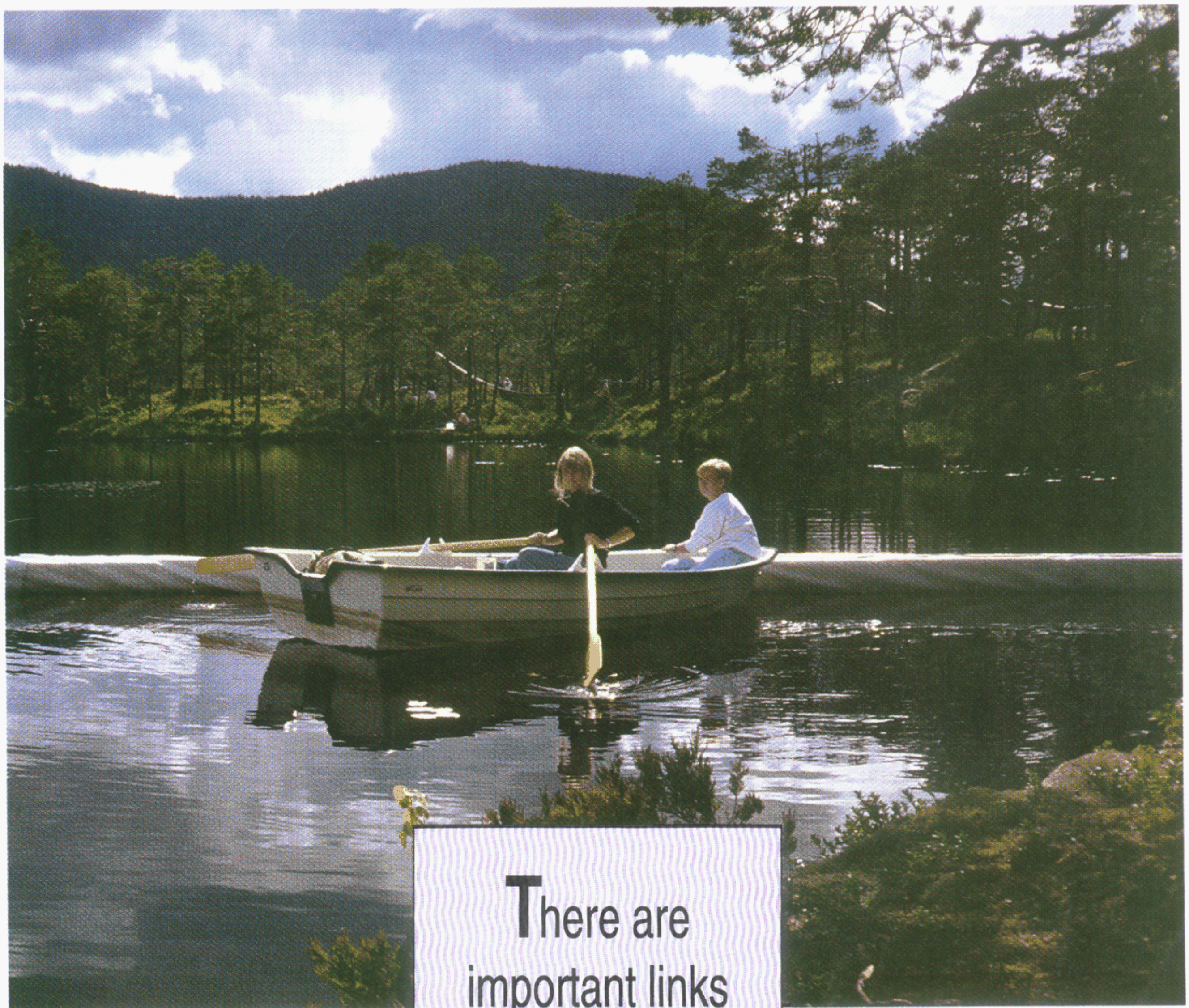
The NITRogen Saturation EXperiments (NITREX) project focuses on the impacts of nitrate and ammonium on forest ecosystems (*6*). NITREX includes 11 separate large-scale nitrogen addition or removal experiments at nine sites that span the European gradient in nitrogen deposition, from < 5 kg N ha^{-1} per year in western Norway to > 50 kg N ha^{-1} per year in the Netherlands.

At each site, precipitation, throughfall, soil, soil solution, and runoff (catchments only) are being monitored, before and after initiation of the experimental manipulations. Nutrient status and nutrient cycling are studied by periodically examining litterfall, needle composition, soil organic matter composition and mass, and fine root biomass. Nitrogen-15 tracer studies are under way at several sites to follow the fate of added nitrogen throughout the forest ecosystems. Results from the various studies are used to develop and test process-based models for nitrogen in coniferous forests. Model outputs are intended to provide a basis for determining critical loads for European forest and freshwater ecosystems.

The overall objective of the program is to obtain direct experimental data at the ecosystem level of nitrogen saturation from atmospheric deposition, and subsequent ecosystem recovery. Questions regarding the threshold for nitrogen saturation, critical loads, and reversibility are addressed by means of a matrix of experimental manipulations that includes increasing nitrogen inputs to some forest ecosystems and excluding ambient nitrogen (and sulfur) inputs to other forest ecosystems.

In the EXperimental MANipulations of Forest Ecosystems in Europe (EXMAN) project, research is conducted at five sites in Denmark, Germany, and the Netherlands, with a control site in Ireland (*7*). Major objectives of the program are quantification of element biogeochemical cycling, biomass turn-

0013-936X/93/0927-1482$04.00/0



over, and the effects of atmospheric deposition on forest ecosystems. Comparable manipulations will be conducted within similar forest types across a range of atmospheric inputs. Preliminary results from some manipulations suggest that the hydrochemical models are particularly in need of improved treatment of biological processes (*8*).

Research going on at more than 40 catchment sites in 10 countries is linked within the umbrella European Network of Catchments Organized for Research on Ecosystems (ENCORE) project. The sites are located within a broad range of environmental and atmospheric pollution conditions from northern Norway to southeastern Spain and from the western United Kingdom to the boundaries of what was formerly Czechoslovakia (*9*).

ENCORE was established primarily to develop, improve, and test process-based models of ecosystem response to perturbations. The basic approach is threefold:

> There are important links between nitrogen deposition and the release of greenhouse gases

- Evaluate models across varying catchment types using baseline data collected at all sites and identify weaknesses in the models.
- Improve the level of scientific understanding of key processes by conducting detailed process studies at selected sites and improve models with these data.
- Test and validate models by using catchment manipulations and unplanned perturbations, including liming, acid additions, fertilization, acid input reductions, clearcutting, fire, and forest dieback.

Whole-system nitrogen enrichment

Ambient nitrogen, and in some cases sulfur, deposition is being augmented at research sites throughout Europe. Typically, the experimental approach involves acid application during rainfall by means of sprinkler systems, using chemically altered water from a nearby lake or spring as a carrier for the acid or acid precursor. Several studies are highlighted below.

Sogndal, Norway. The Sogndal site in western Norway was part of the Reversing Acidification in Norway (RAIN) project (*10*). One of the small catchments (SOG4) has received a 1:1 mixture of sulfuric and nitric acid additions since 1984. The region receives only 4 kg S and 2.5 kg N ha^{-1} per year of atmospheric deposition.

Addition of H_2SO_4 and HNO_3 at SOG4 has caused significant changes in runoff chemistry. During the first five years of treatment, nitrate concentrations in runoff at

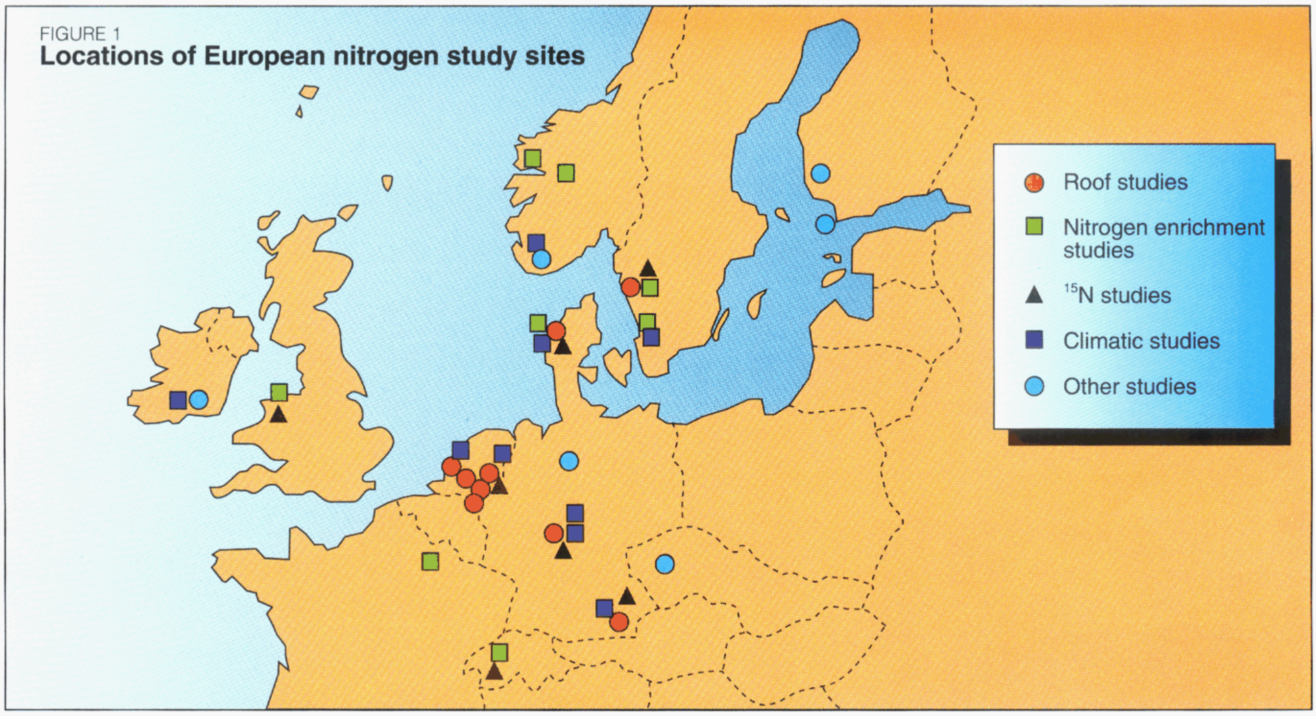


FIGURE 1
Locations of European nitrogen study sites

SOG4 were elevated in comparison with concentrations at the control sites (SOG1 and SOG3) only immediately after acid applications. Since 1989, however, the NO_3^- concentration in runoff has been chronically high. Alkalinity and pH decreased in parallel fashion at the H_2SO_4- treated catchment (SOG2) and the H_2SO_4 + HNO_3-treated catchment (SOG4) (*10*).

The RAIN project ended in 1991, and the site was at that point included within NITREX. Sogndal represents the catchment receiving lowest deposition within the NITREX framework, and is also the only nonforested (alpine) catchment in the project (*5*).

Humic lake acidification

Dissolved humic substances exert a large influence on the acid–base chemistry of drainage and surface waters, particularly dilute systems. It has also become increasingly evident in recent years that humic substances can influence the responses of terrestrial and aquatic ecosystems to nitrogen and sulfur inputs. In response to this growing realization and the scarcity of empirical data with which to quantify the major effects, the Norwegian Institute for Water Research (NIVA) launched the HUMic Lake Acidification EXperiment (HUMEX) project in 1988 (*11*).

Dystrophic Lake Skjervatjern was separated into two basins by means of a plastic curtain installed from the middle of the natural outlet to the opposite shore. Artificial acidification with sulfuric acid and ammonium nitrate was begun two years after installation of the curtain. Acids are applied to the treatment half of the lake and its drainage basin, during periods of precipitation by means of a sprinkler system. The annual target loadings for sulfate and total nitrogen are 63–66 kg/ha and 17–32 kg/ha, respectively.

Preliminary results indicate that most of the applied sulfur and nitrogen is taken up by the terrestrial catchment. Hydrology appears very complex at the site, and this may make catchment modeling efforts difficult. Lake water concentrations of sulfate, nitrate, and ammonium have all increased with the treatment, but pH and DOC have not yet been substantially affected (*11*).

Aber, Wales. Most forests in the United Kingdom are thought to immobilize a high proportion of incoming atmospheric nitrogen. One exception is the Beddgelert Forest in North Wales, where nitrogen outputs are higher than inputs by bulk precipitation. The Aber forest study component of NITREX was designed to examine how a forest in this region would process additional loadings of nitrogen. Beddgelert Forest is still immobilizing some incoming atmospheric nitrogen.

The experimental design includes three replicate plots that receive each of five treatments in a randomized block design (*6*). The treatments began in 1990 and include control, added water, added sodium nitrate (35 and 75 kg N ha^{-1} per year), and ammonium nitrate (35 kg N ha^{-1} per year). Initial results show a rapid increase in NO_3^- in soil solution for both of the sodium nitrate treatment levels, although about 75% of the added nitrogen is being immobilized on site or denitrified. In contrast, essentially all of the added nitrogen at the ammonium nitrate plots has been immobilized or denitrified with little change in nitrate leaching.

Roof studies

An important tool that has developed in recent years for the study of ecosystem processes and the impacts of atmospheric deposition at the ecosystem level is the construction of transparent roofs over entire mini-catchments or forested plots. The roof emplacement technique was pioneered at Risdalsheia, Norway, in 1983 in the RAIN project (*10*). A number of additional roof studies have started in Europe during the past five years, with roofs ranging in size from ~300 m^2 to 0.6 ha. In most cases the roofs are constructed below the canopy in well-developed forests. Runoff from the roof is collected, chemically altered, and reapplied beneath via sprinklers. The technique allows simulation of drought and decreased atmospheric deposition to entire terrestrial systems. Ongoing studies at several sites are described below.

Gårdsjön, Sweden. Whole-catchment exclusion of incoming ambient atmospheric pollution reached its apex with construction of the large (0.6 ha) roof at the Gårdsjön site in Sweden in 1990 (see photo) (*12*). The clear plastic roof intercepts atmospheric deposition 2–4 m above the ground. Approximately 350 Norway spruce trees protrude through the roof. The roof experiment excludes about 20–30 kg S ha^{-1} and 15–20 kg N ha^{-1} ambient atmospheric deposition.

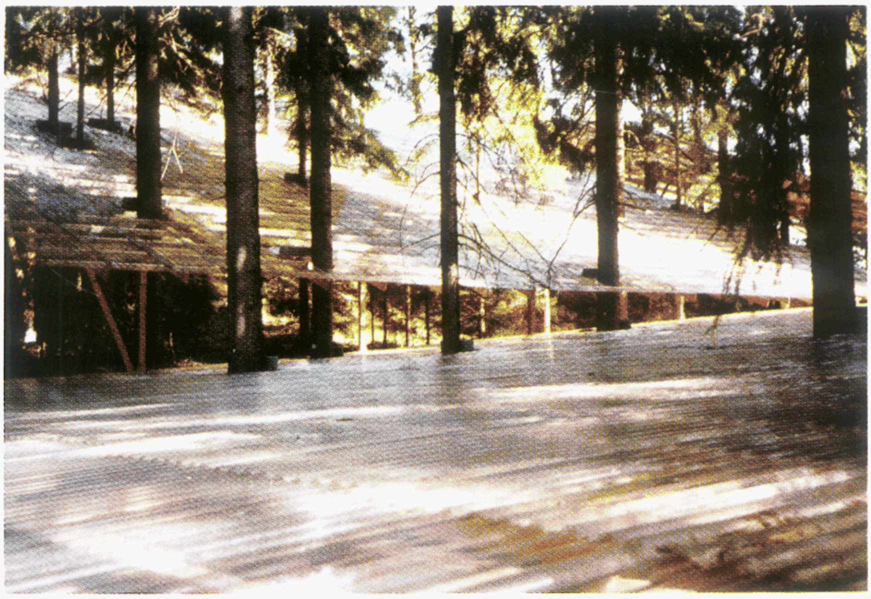
Approximately 20 different and coordinated subprojects are being conducted at Gårdsjön, including input–output budgets for all major ions (including mercury and other heavy metals); water pathways through the soil; vegetation and fine root effects; chemistry of soil, soil water, and groundwater; soil processes (e.g., sulfur retention, weathering); isotope studies for partitioning of sulfur, nitrogen, mercury; wet, dry, and fog deposition processes for sulfur, nitrogen, mercury; trace gas emissions; and geochemical modeling and model testing.

Ysselsteyn and Speuld, Netherlands. The Netherlands receives extremely high levels of nitrogen deposition (50–100 kg N ha^{-1} per year). The major objective of the ongoing studies at Ysselsteyn and Speuld, within the context of EXMAN, is to investigate the potential reversibility of the existing nitrogen saturation. Nitrate is currently being exported in large quantities from the soils into the groundwater at these sites.

A transparent roof, 2–3 m above the ground, was constructed at each of these sites during the winter of 1988–89 (*13*). A reduction in the nitrogen content of young needles at the "clean" roof plot has not appeared so far. Among several explanations for this outcome is the possibility that trees continued to take up large amounts of nitrogen with their aerial parts (above the roof).

Klosterhede, Denmark. The Klosterhede Plantation in western Denmark, a 73-year-old even-aged Norway spruce (*Picea abies*) stand, is included in the NITREX and EXMAN projects (*6, 14*). Three study plots (each containing about 25 trees) have been established beneath the roof; a fourth plot outside the roof serves as a control. Treatments include summer drought, irrigation with the optimal amount of water and removal of incoming acid deposition, and irrigation with the optimal amount of water plus optimal nutrition with macro- and micronutrients ("fertigation").

Significant biological response has been observed as the treatments have proceeded. Biomass increment, photosynthetic activity, needle element content, cone production, root development, ground vegetation, and microbial activity have all changed. Results to date show large variations for individual trees, core samples, and annual diameter growth. Despite the variability, however, higher tree growth rates have been observed in the fertilized and irrigated plots since 1988 (*14*).



View of part of the roof at Gårdsjön, Sweden. This 0.6-ha roof catchment represents the largest deposition exclusion experiment in the world.

Plot studies

Plot studies have been going on in a number of areas throughout Europe (Figure 1) to investigate linkages between atmospheric inputs, climatic conditions, and nutrition in forest stands. Some studies have examined forest responses over long periods of time (up to 20 years) (*15*). Of particular interest is the study of ecosystem processes and forest health at variable distances downwind from large nitrogen point sources.

Ferm and co-workers (*16*), for example, investigated Scotch pine (*Pinus sylvestris*) forests close to three fur animal farms in Finland and a control forest stand > 850 m from the point sources. Local deposition under the forest canopy was high (33 kg N ha^{-1} per year), compared with regional ambient deposition (< 5 kg N ha^{-1} per year). Forest damage close to the fur animal farms resembled growth disturbances related to nutrition or excessive nitrogen fertilization, and stand damages clearly decreased with distance from the farms.

Studies adjacent to nitrogen emission point sources can be very useful, particularly where the regional nitrogen deposition is low. These point sources provide nearly the equivalent of whole-system nitrogen addition experiments without the expense and logistical difficulties of the experimental manipulations. In addition, the study of a number of such point sources, which have been in operation for varying amounts of time, might provide useful information about the time scales of ecosystem response.

^{15}N tracer experiments

Studies of the ^{15}N abundance of soil or vegetation samples collected over time, or of samples from nitrogen enrichment studies, are an important tool for evaluating whether the ecosystem is sequestering nitrogen or losing it (*17, 18*). The approach is potentially useful because it includes the effect of nitrogen loss via denitrification, which is difficult to measure separately in the field. The large pools of nitrogen that are already present in vegetation and the forest floor make it difficult to detect changes in pool size in response to experimental treatments. The ^{15}N stable isotope approach helps to address this problem.

Stable isotope studies are being conducted at a number of research sites, in particular in conjunction with NITREX (*6*) (Figure 1). The NITREX studies will include quantification of the ^{15}N abundances in trees, ground vegetation, soil, forest floor, roots, litter, mineralization samples, microbes, precipitation, soil solution, and outflow. These studies will provide background data on both ^{15}N abundance and variability across the pollution gradient. Subsequently, ^{15}N enrichment studies will be conducted at the study sites.

Climatic interactions

It is often difficult to separate the effects of excess nitrogen deposition from climatic effects. For example, it has been proposed that high nitrogen loadings result in increased susceptibility of trees to drought and frost. Elevated deposition of nitrogen can affect the water uptake of trees, via increased shoot/root ratio, thereby increasing water demand; shift in root growth from mineral soil to upper organic horizon, thereby increasing susceptibility to drought; and reduced fine-root length and biomass.

The interactions between climate change and acidic deposition, as well as the direct effects of climatic manipulations on a subalpine coniferous forest ecosystem, will be investigated in the CLIMate Change EXperiment (CLIMEX) project, which is scheduled to begin this year (*19*). The major objective of CLIMEX is to quantify the impacts of atmospheric CO_2 enrichment and temperature increase on ecosystem response, especially the plant–soil–water linkages and processes. The approach will involve whole-catchment manipulations of temperature and atmospheric CO_2 concentration at the Risdalsheia roofed catchment in southern Norway, formerly part of the RAIN project.

Conclusions

There has been an enormous increase during the past several years in the amount of research being conducted in Europe on the effects of atmospheric deposition of nitrogen on aquatic, and especially terrestrial, ecosystems. The experimental approach has shifted heavily into whole-ecosystem experimental manipulations, which are being conducted across gradients of atmospheric deposition and other environmental factors. Manipulations are focused primarily on coniferous forest ecosystems and involve increasing ambient deposition of sulfur and nitrogen; excluding ambient deposition via the construction of roofs over entire forested plots or catchments; and manipulating climatic factors, especially water availability. Experiments are designed to continue for long periods (i.e., 5–10 years) and are augmented by detailed, process-level studies at the manipulation sites. Results of the broad-scale and detailed studies are being used to build, test, and validate mathematical models that simulate nitrogen processing, nutrient cycling, and water regulation in coniferous forest ecosystems under varying depositional and climatic regimes. Ultimately, these models will be used to predict nitrogen saturation, estimate the critical loads of nitrogen for European forests, and specify emission controls needed to protect European forests and surface waters from the detrimental effects of excess nitrogen deposition.

Acknowledgments

This work was funded by the National Acid Precipitation Assessment Program (NAPAP). It has not been subjected to NAPAP or other federal agency review, and no official endorsement is implied. Derek Winstanley provided helpful advice and assistance.

References

(1) Aber, J. D. et al. *Ecol. Appl.* **1991,** *1*(3), 303–15.
(2) Kahl, J. S. et al. *Environ. Sci. Technol.* **1993,** *27*, 565–68.
(3) Husar, R. B.; Sullivan, T. J.; Charles, D. F. In *Acidic Deposition and Aquatic Ecosystems: Regional Case Studies*; Charles, D. F., Ed.; Springer-Verlag: New York, 1991.
(4) Tietema, A.; Bouten, W.; Wartenbergh, P. E. *For. Ecol. Mgmt.* **1991,** *44*, 53–61.
(5) Steudler, P. A. et al. *Nature* **1989,** *341*, 314–16.
(6) *The NITREX Project (Nitrogen saturation experiments)*; Dise, N. B.; Wright, R. F., Eds.; Ecosystems Research Report 2; Commission of the European Communities; Brussels, Belgium, 1991; p. 101.
(7) Rasmussen, L. C. Presented at the International Symposium on Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems—Approach, Methodologies, Findings; Copenhagen, Denmark, May 18–20, 1992.
(8) Beier, C. et al. In *Proceedings of the International Symposium on Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems;* Rasmussen, L.; Brydges, T.; Mathy, P., Eds.; Commission of European Communities: Copenhagen, 1993; pp. 138–54.
(9) Hornung, M. In *Proceedings of the International Symposium on Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems—Approach, Methodologies, Findings;* Rasmussen, L.; Brydges, T.; Mathy, P., Eds.; Commission of European Communities: Copenhagen, 1993; pp. 37–45.
(10) Wright, R. F. "RAIN project. Report for the Years 1988, 1989, 1990"; Acid Rain Research Report 24/91; Norwegian Institute for Water Research: Oslo, Norway, 1991; p. 81.
(11) Gjessing, E. In *Proceedings of the International Symposium on Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems—Approach, Methodologies, Findings;* Rasmussen, L.; Brydges, T.; Mathy, P., Eds.; Commission of European Communities: Copenhagen, 1993; pp. 277–83.
(12) Dise, N. B. et al. "NITREX Project—Gårdsjön Status Report for 1990–91"; Norwegian Institute for Water Research: Oslo, Norway, 1992.
(13) van Dijk, H.F.G.; Boxman, A. W.; Roelofs, J.G.M. "Interim Project Report 1988–91"; Department of Ecology, University of Nijmegen: Nijmegen, The Netherlands, 1992; p. 40.
(14) Rasmussen, L.; Hansen, K. *Air Pollution Effects on Forests Examined by Manipulation of the Forest Ecosystem*; Technical University of Denmark: Lyngby, 1992.
(15) Tamm, C. O.; Högberg, P. In *Proceedings of the International Symposium on Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems—Approach, Methodologies, Findings;* Rasmussen, L.; Brydges, T.; Mathy, P., Eds.; Commission of European Communities: Copenhagen, 1993; pp. 272–76.
(16) Ferm, A. et al. In *Acidification in Finland;* Kauppi, P. et al., Eds.; Springer-Verlag: Berlin, 1990; pp. 635–68.
(17) Kjønaas, O. J. et al. In *Proceedings of the International Symposium on Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems—Approach, Methodologies, Findings*; Rasmussen, L.; Brydges, T.; Mathy, P. Eds.; Commission of European Communities: Copenhagen, 1993; pp. 235–37.
(18) Gebauer, G.; Schulze, E-D. *Oecologia* **1991,** *87*, 198–207.
(19) Jenkins, A. et al. In *Proceedings of the International Symposium on Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems—Approach, Methodologies, Findings;* Rasmussen, L.; Brydges, T.; Mathy, P., Eds.; Commission of European Communities: Copenhagen, 1993; pp. 71–77.

***Timothy J. Sullivan** is president of E&S Environmental Chemistry, Inc., an applied research firm in Corvallis, OR, that specializes in water quality and the environmental effects of air pollutants and land use. He received an M.A. degree in biology from Western State College of Colorado and a Ph.D. in biological sciences from Oregon State University. His research has focused on the effects of air pollution on aquatic and terrestrial ecosystems.*