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Acid rain in Europe and the United States: an update

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Abstract

This paper discusses the evolution of science and policies to control acid rain in Europe and the United States over the past several decades. Acid rain gained prominence in the late 1960s because of its perceived effects on ecosystem integrity. Extensive research efforts in both Europe and the United States, however, have concluded that the effects of acid rain—at least those on terrestrial ecosystems—were less serious than originally believed. More recently, interest in controlling acid rain precursors stems primarily from health concerns, particularly their effects in the form of fine particulate matter. The paper discusses the emergence of acid rain as an environmental concern, scientific evidence about the effects of acidic deposition on natural ecosystems, US and European acid rain control policies, studies of the costs and benefits of reducing acid rain, and different policy contexts in Europe and the United States.

Keywords: Acid rain; Acid rain policy; Acidic deposition; Air pollution

> And now worse visions of a viler age Loom through the darkness of the future's night. A sickening fog of smoke from British coal Drops in a grimy pall upon the land, Befouls the vernal green and chokes to death Each lovely shoot, drifts low in poisoned clouds, And steels the sun and daylight from the place, Or falls, like that volcanic ash which rained On the doomed cities of antiquity
>
> Henrik Ibsen, Brand, 1866

1. Introduction

Concern about harmful effects of air pollution resulting from sulphur emissions is certainly not a recent phenomenon. Complaints about the infamous air pollution in London, partly linked to sulphur dioxide (SO_2) and sulphate aerosols, are known at least back to the thirteenth century (Brimblecombe, 1987). John Evelyn (1661) described many of the effects of air pollution in his book *Fumifugium*. Acid rain seems to have first been mentioned by the pharmacist Ducros in 1845. However, it was Robert Angus Smith (1872) who first conducted detailed studies of acid rain and described many of its potentially harmful effects.

Early concern with air pollution focused on local impacts, although the possibility of regional scale impacts was also recognized. Brøgger (1881) first established the occurrence of long-range transport of pollutants from the United Kingdom to Norway. Dannevig (1959) suggested that acidic deposition was causing fish kills in Norwegian bodies of water. However, acid rain gained considerably more attention when Odén (1967, 1968) stated that large-scale acidification of surface waters in Sweden could be attributed to pollution from the United Kingdom and central Europe. Odén first published his findings in a Swedish daily newspaper (Odén, 1967), causing much concern in Sweden. About a decade later, acid rain gained attention in the United States when Schofield reported the discovery of acidic lakes and the possible loss of native brook trout in the Adirondack Mountain region of New York (Schofield, 1976). The issue gained considerable notice because of the absence of significant air pollution sources in the Adirondack region. The acidification problem in northeastern United States was (and still is) attributed principally to atmospheric transport of emissions from sources located in the midwestern region of the country.

Acid rain (more correctly, acidic deposition) is one of the foremost examples of regional air pollution and has received worldwide attention because acidification damages are often the result of atmospheric transport of sulphur and nitrogen emissions across state and/or national boundaries. In Europe, acidic deposition crosses national boundaries, with Scandinavian countries (principally) concerned about acidification

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damages resulting from emissions coming from the United Kingdom and the central and eastern European continents. In the United States, northeastern states are concerned about emissions transported primarily from states in the Midwest and, to a lesser extent, from southeastern Canada.[1] Because of its transboundary nature, controlling acid rain is very difficult politically.

In both Europe and the United States, the primary motivating factor for regulations to control SO_2 emissions before the 1970s was concern for local public health. Damages to natural ecosystems received little or no attention. However, partly because measures to control acid rain precursors were insufficient, and partly because local effects of SO_2 emissions were often mitigated by increasing stack heights of stationary sources, long-range transport of SO_2 increased over time. The result was more acidic deposition—and possible acidification damages—in regions downwind from sources. When fish losses and possible terrestrial damages were reported in sensitive regions that had no apparent local pollution sources, acid rain became a major environmental issue on both sides of the Atlantic. Since the 1970s, acid rain has remained in the public spotlight in both Europe and the United States and recently has emerged as an important problem in other regions such as Southeast Asia, particularly China. However, the primary motivation for more stringent controls on SO_2 and, to a lesser extent, nitrogen oxide (NO_x) emissions is now shifting back to adverse health effects rather than damages to natural ecosystems.

This paper considers how issues linked to and policies addressing acid rain in Europe and the United States have evolved over the past 30 years. The next section summarizes basic evidence about the causes and effects of acidic deposition, focusing on its impact on natural resources, particularly soils, aquatic ecosystems, and forests. The third section reviews the evolution of air pollution policies to address acid rain in United States and Europe from the 1960s to the present. This section also discusses the role of science (including economic analysis) in policy making for acid rain control and possible future directions for acid rain polices. Conclusions are presented in the final section.

2. Background

2.1. Causes and effects of acidic deposition

Linkages between emissions, atmospheric transport and deposition, and environmental responses from acidic deposition have been fairly well understood for some time.[2] Acid rain is caused by emissions of SO_2 (principally from fossil-fuel power stations, metal smelters, and other stationary sources) and NO_x (from mobile sources, industrial sources, and power plants) forming sulphuric and nitric acid in precipitation. The gases (or aerosols) may also be deposited as dry deposition, which often dominates wet deposition in areas close to emission sources. In addition to wet and dry deposition, the total deposition may include a contribution from acidic mist (sometimes denoted occult deposition). Rainwater in equilibrium with carbon dioxide (CO_2) in air (and with no other species affecting pH) is slightly acidic, with a pH of 5.6, while neutral water exhibits a pH of 7.0. However, even under pristine conditions, rainwater is often more acidic due to natural emissions of SO_2, NO_x or organic acids. Typical pH values of acid precipitation caused by anthropogenic emissions may be in the range of 3.5–5.0. In contrast, ammonia (NH_3) emissions will neutralize the precipitation or even make it alkaline, but may cause soil acidification through nitrification.

In connection with negotiations concerning reductions in emissions, there was much discussion in the early 1980s about source–receptor relationships, particularly whether there is a linear relationship between emissions and acidic deposition.[3] Deviation from linearity is most likely due to wet deposition. In addition to wind direction and distance from the source, wet deposition at a given receptor region depends on a number of other factors, including the amount of precipitation and rate of SO_2 oxidation. Although the emission–deposition relationship clearly is not strictly linear, the deviations are not very important from a policy viewpoint. The substantial reduction in sulphur emissions in Europe (see below) has greatly affected deposition in Scandinavia. Thus, sulphur deposition at a site in southernmost Norway was reduced by 50% between the 1976–1985 and 1995–2001 time periods (Aas et al., 2002). In the United States, substantial reductions in sulphur emissions during the 1990s have contributed to a continuing long-term decline in sulphate deposition (Stoddard et al., 2003).

The acid rain precursors (SO_2 and NO_x) and NH_3 may form secondary pollutants such as particles and the nitrogen species may in reactions with organic compounds contribute to ozone (O_3) formation. The gases, particularly SO_2 and O_3, may cause vegetation damage. Health effects are mainly related to the precursors and secondary pollutants. Corrosion of many materials increases with the SO_2 concentration in air; ozone and rain acidity may also contribute to materials damages. Visibility can be affected by the formed aerosols. In addition, sulphate particles generally have a climatic effect. The most focused effects of acidic deposition—acidification of water and soils with accompanying effects on biota—are discussed in some detail below.

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[1] Pollution from sources in the United States also contributed to acid rain damage in Canada, causing a significant dispute between the governments of Canada and the United States during the 1980s. For discussion of the Canadian-US dispute, see Schmandt et al. (1988).

[2] For an early study of the process of acidic deposition in eastern North America, see National Academy Press (1986).

[3] For example, Chester (1986) at the Central Electricity Research Laboratories in Great Britain wrote: “To be able to quantify the response of acid deposition around the fringe of Europe to reductions in European sources, we must clarify the extent of non-proportionality . . . .”

2.2. Regions affected by acidic deposition

Regions that have been most affected by acidic deposition include Europe, eastern North America, and Southeast Asia, especially central and southern China (Kuylenstierna et al., 2001). Sulphur emissions have played the dominant role in acidic deposition in these regions. However, there have been large reductions in SO_2 emissions in Europe and North America during the last two decades: by about 65% in Europe and 40% in the United States from 1980 to 1999. NO_x emissions in Europe increased from 1980 to 1990, but decreased by nearly 30% from 1990 to 2001 (Vestreng, 2003). Emissions of NO_x in the United States remained relatively stable from 1980 to 1999 (USEPA, 2001). Sulphur emissions in China decreased in the late 1990s, increased from 1999 to 2000, and remained stable up to 2002 (Li and Gao, 2002; Zhou et al., 2003). NO_x emissions are more difficult to curb than sulphur emissions, and reduction of ammonia emissions is particularly challenging (Kaiser, 2001). Ammonia emissions have increased greatly over the last couple of decades, particularly in some Asian countries due to increased use of fertilizers and greater amounts of animal waste (Galloway and Cowling, 2002).

2.3. Effects of acidic deposition on soils

Since soil acidification[4] may in turn affect vegetation and acidification of water is strongly related to soil properties, it is important to understand the effects of acidic deposition on soils. The effects on soils depend strongly on the fate of sulphate and nitrate. If these anions leach out of the soil, they must necessarily be accompanied by cations. If the soil is acidic, a substantial fraction of cations in soil water and leachate is aluminum (Al) ions and H^+; a less acidic soil will leach more base cations (in particular, Ca^{2+} and Mg^{2+}). In the former case, acidification of surface waters may occur and the soil water may become so acidic and contain so much aluminum that vegetation is affected. Loss of base cations will result in soil acidification if it is not compensated by cations in the deposition or released through weathering.

In many young soils, such as those found in the Nordic regions, sulphate is fairly mobile, although some sulphur accumulation probably occurred during the long period of increasing acidic deposition. Old soils containing a large fraction of secondary clay minerals, such as those found further south, strongly adsorb sulphate. In such soils, a sulphate front may be created and the concentration in leachate may remain relatively unchanged over long periods of time (decades) until the front has penetrated the soil profile. Nitrate is quite mobile in soils, but is taken up by vegetation. However, when nitrate deposition is sufficiently large, a considerable part of the nitrate may leach out (Wright et al., 2001).

Soil acidification has occurred in Europe (Tamm and Hallbäcken, 1988), eastern North America (Watmough and Dillon, 2003), and likely also in China (Dai et al., 1998). Since a number of factors may cause soil acidification (including vegetation changes), it is difficult to determine the contribution from acidic deposition. There is also uncertainty about the time scale over which effects on soils might occur.

2.4. Effects on aquatic ecosystems

Water acidification resulting from acidic deposition occurs in areas with acidic soils because most precipitation falls on terrestrial parts of the catchment, so soil properties strongly affect the percolate before it enters a body of water. In Europe, water acidification has been most serious in Scandinavia, where bodies of water (typically, inland ponds, lakes, and streams) with pH below 5 are common. In Norway, acidic deposition caused the loss of fish populations in thousands of lakes from about 1950 until recently (Hesthagen et al., 1999). The problem has also occurred to some extent in other parts of Europe and in certain regions of the eastern United States and Canada.

There have been considerable improvements (measured by increased acid neutralization capacity, ANC,[5] or pH) in acidified water bodies in Europe as a result of reduced acid precursor emissions in recent years (Stoddard et al., 1999; Skjelkvale et al., 2001; Evans et al., 2001). Stoddard et al. (1999) reported reduced acidification in water bodies in only one of five areas in North America (New England) despite a considerable reduction in sulphur emissions during the 1990s. However, a more recent study (Stoddard et al., 2003) shows improvements in water bodies in several areas in the United States, which did not show recovery in the previous study, including Adirondack lakes. Recovery rates in areas with similar reductions in sulphur deposition differs greatly depending on soil thickness, sulphate adsorption/desorption, leaching of base cations, and trends in deposition of reactive nitrogen.

2.5. Models for acidification of soils and water

Research efforts to develop simulation models for soils and waters exposed to acid deposition have been very extensive, but it is outside the scope of this paper to give a comprehensive overview of this work. Early efforts include Christophersen et al. (1982), Cosby et al. (1985), Gherini et al. (1985), and Reuss and Johnson (1986).[6] Although differing in complexity, the models developed in these efforts

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[4] Soil acidification may be measured as decrease in amounts of exchangeable base cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) or decrease in soil pH. Increased mobilization of aluminium is an important result of soil acidification (Reuss and Johnson, 1986).

[5] ANC is a measure of the ability of water to neutralize inputs of acids. It is measured as the amount of strong acid needed to change pH to that of the CO_2 equivalence point (about 4.5).

[6] For an overview, see Reuss et al. (1986).

had important basic assumptions in common. More recent studies (Christophersen et al., 1990; Kirchner et al., 2000) have contributed to better understanding of water flow paths, a prerequisite for modeling surface water chemistry and understanding acidification mechanisms. However, the reliability of such models in predicting changes in water and soil that would result from changes in acidic deposition is still unsatisfactory.

2.6. *Effects on forests*

Possible effects of acidic deposition (and its precursors) on forests have been the topic of intensive research efforts in both Europe (UN/EC, 2002) and the United States (NAPAP, 1991a, 1998). Nonetheless, quantitative relationships between primary pollutants and forest damage have been difficult to obtain. Vegetation damages may be caused by direct exposure to gaseous or particulate air pollutants or indirectly through soil acidification. Direct damage from SO_2 emissions is very likely in some regions. Other possible mechanisms for forest damage include high concentrations of ozone and other photo oxidants and, in some areas, hydrogen fluoride in the air. Indirect effects from elevated levels of toxic aluminum in soil water, leaching of plant nutrients (particularly magnesium) from soils, or reduced availability of phosphorus may also be responsible for reduced forest vitality. Acidic mist or acidic cloud water can reduce tolerance of certain tree species to cold. In most pristine forests, increased deposition of nitrogen will increase growth rates, but if nitrate deposition becomes too high it may result in damage due to soil acidification, lack of other nutrients, or increased sensitivity to other stress factors. Vegetation damage is most likely a combined effect of anthropogenic and natural stressors (e.g., drought, frost, and pests).

In Europe, assessment and monitoring of effects of air pollution on forests have been carried out in a joint UN-EC program since the late 1980s (UN/EC, 2002). Except for some areas in Eastern Europe, where direct effects of SO_2 probably have played an important role in causing damages to forests, there are no clear long-term trends that can be related to acidic deposition. Fortunately, the dramatic forest dieback feared by some scientists in the 1980s never materialized. Recent improvements in tree vitality in some areas (e.g., Poland and the Czech Republic) have been related to both decreased pollution and favorable weather conditions.

To date, investigations of possible effects of acidic deposition on forests in northeastern United States and in Canada have focused on red spruce and sugar maple. There is evidence that acidic deposition has caused dieback of red spruce by decreasing their tolerance to cold (Driscoll et al., 2001; Vann et al., 1992). Damage to sugar maple may in some localized areas be caused, at least partially, by loss of base cations (Ca^{2+}, Mg^{2+}) from the soil (cf. section on soil acidification). Long-term changes to forests are possible due to multiple stress factors and/or acidic deposition (NAPAP, 1991a).

3. Acid rain control policies in Europe and the United States

Policies to address air pollution have changed dramatically over time in response to changing public concerns. Until the mid-twentieth century, dust and soot associated with the burning of coal often led to severe local problems, including acute health effects. Two incidents marked the beginning of modern efforts to assess and deal with the health threats from air pollution. The infamous smog episode in London in December 1952 resulted in the deaths of several thousand people and provided the impetus for measures to improve local air quality in the United Kingdom. A similar occurrence in the Monongahela River town of Donora, Pennsylvania in October 1948 caused 20 deaths and illness and/or hospitalization of 7000 people. The Donora episode resulted in the first meaningful federal and state laws to control air pollution in the United States.

In the 1970s and 1980s, the effects of acid rain on natural resources and ecosystems became an issue of considerable public concern in both northwestern Europe and northeastern United States. During this period, the focus of environmental protection efforts shifted from almost exclusive preoccupation with the effects of air pollution on public health to its effects on the integrity of natural ecosystems. The regional nature of acidic deposition and evidence of long-range atmospheric transport of air pollutants also became evident. Nonetheless, because of the disparity between the geographic areas responsible for emissions and those bearing the effects, revamping policies to deal with sulphur and nitrogen emissions on a regional basis was difficult politically.

In the United States, acid rain gained attention with the reporting of acidic lakes in the Adirondack Mountain region in New York (Schofield, 1976). Several northeastern states and the province of Ontario, Canada, sued the U.S. Environmental Protection Agency in 1980 to take action to control acid-precursor emissions emanating from states in the Midwest. In Europe, there was pressure in the 1970s from Sweden and Norway based mainly on concern for water acidification, but this initially made little impression. An interesting illustration of the controversy about acid rain in Europe is found in an editorial in Nature in 1977 entitled *Million dollar problem—billion dollar solution?* (Nature, 1997). The editorial stated that the cost of fish kills in Norwegian bodies of water due to acid rain might have been about US$ 1 million.[7] The editorial suggested that Britain should supply Norway with limestone to be added to lakes. The conclusion was:

> . . . the Norwegian government would be foolish to reject such a proposal out of hand—as seems quite likely.

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[7] The basis for this number is not clear but it is presumably based on the commercial value of the fish. The economic value of lost recreational opportunities and other sources of economic value were clearly not taken into account.

> An insistence on removing pollution at source calls for so much investment and will generate so much international ill will that any more flexible solution must first be considered.

3.1. US policy for acid rain control

In the United States, emissions standards for SO_2 and NO_x have been set by the Federal government under auspices of the Clean Air Act (CAA), first adopted in 1970. The CAA set statutory deadlines for compliance with the nationwide ambient air quality standards (NAAQS) and directed states to develop implementation plans applicable to stationary air pollution sources in their state. The CAA was amended in 1977 primarily to set new goals (dates) for achieving attainment of NAAQS since many areas of the country had failed to meet the statutory deadlines.

While concern with public health was the primary motivation for establishing national air quality standards, the effects of air pollution on ecosystems and the regional scale of particular air pollutants (particularly acid rain precursors) gained notice later in the 1970s. In response to pressure from governments in the affected areas, the scientific community, environmental organizations, the media, and the general public, Congress formed the National Acid Precipitation Assessment Program (NAPAP) and mandated NAPAP to conduct a 10-year scientific, technological, and economic study of the acid rain issue under the Acid Precipitation Act of 1980 (PL 96-294). The purpose of the study was to inform public policy by providing information on:

- specific regions and resources affected by acidic deposition,
- how and where acid precursor emissions are transformed and distributed,
- whether the effects are extensive and require mitigation, and
- what emissions control technologies and mitigation options are available to reduce acidic deposition.

One of the results of this effort was the National Acid Precipitation Assessment Program's *Integrated Assessment* (NAPAP, 1991a) and 27 *State-of-Science and State of Technology* (SOS/T) reports that documented scientific and technical information for specialized audiences (NAPAP, 1991b). The *Integrated Assessment* was intended to assess the relationships between acidic deposition and aquatic, terrestrial, and agricultural effects, and the effects of acid deposition on materials, visibility, and human health, and was to be a first step toward a comprehensive cost-benefit analysis of the issue (NAPAP, 1991a, p. 4). Nonetheless, although effects on human health, materials, and visibility were also studied, the effects of acidic deposition on aquatic and terrestrial resources were clearly the major concern of the NAPAP assessment. For example, 16 of the 27 SOS/T reports concerned the effects of acidic deposition, and 7 of those were on surface water chemistry and effects, 3 were on forestry and vegetation responses, 3 were on materials, 2 were on health effects, and 1 was on visibility.

The principal conclusions of the NAPAP assessment regarding effects of acidic deposition on environmental resources were that:

> ... acidic deposition has caused some surface waters to become acidic, particularly in acid-sensitive regions of the United States, and that the rate of change in surface water sulphate concentrations closely paralleled recent changes in regional sulphur emissions and sulphate deposition (NAPAP, 1991a, pp. 11–12), and
>
> There is no evidence of crop damage or widespread forest damage from current levels of acidic deposition, although there are localized areas of forest decline due to multiple stress factors (including acid rain) and acidic deposition may cause long-term changes in forest nutrient status. (NAPAP, 1991a, pp. 45–46)

In a follow-up to the 1990 study, the 1998 NAPAP *Biennial Report to Congress* reported a slightly different conclusion about acidification damages to forests (NAPAP, 1998, p. 3):

> Sulfur and nitrogen depositions have caused adverse impacts on certain highly sensitive forest ecosystems in the United States. High-elevation spruce-fir forests in the eastern United States are the most sensitive. Most forest ecosystems in the East, South, and West are not currently known to be adversely impacted by sulphur and nitrogen deposition. However, if deposition levels are not reduced in areas where they are presently high, adverse effects may develop in more forests due to chronic, multiple decade exposure.

The economic valuation (benefits) component of the 1990 NAPAP assessment was limited in both scale and scope, possibly due to the inherent difficulties of valuing ecosystem effects. It focused on areas where changes in the biophysical effects of acidic deposition had been quantified, including aquatic ecosystems, commercial agriculture, and visibility. Economic values of health, materials, and general ecosystem damages were not included in the NAPAP assessment because of limitations in both data and valuation methodologies. For the areas that were analyzed, the approach was to determine how the economic values of certain resources would be affected as a result of changes in acidic deposition. For aquatic effects, the assessment targeted recreational anglers in cold-water fisheries in one sensitive region—the northeastern Unites States (Maine, New Hampshire, New York, and Vermont). Damages at 1990 levels of sulphur emissions were valued at \$5.3 million to \$27.5 million annually, and it was estimated that reducing deposition by 50% would create economic benefits to recreational anglers ranging from \$20 million to \$31.7 million annually in 2030 (NAPAP, 1991a, p. 383).[8] The potential effect of reduced acidic deposition on agricultural crops was considered to be unknown because SO_2 and NO_x can cause harmful effects on plants, but sulphur and nitrogen are also plant nutrients (NAPAP, 1991a, p. 380). Economic welfare gains to residents of urban areas in eastern United States from improved visibility resulting from a decrease in sulphates from their existing (1990) levels ranged from \$0.3 billion—\$1.2 billion annually for a 20% decrease in sulphates to \$0.6 billion—\$2.5 billion annually for a 40% decrease in sulphates.

After contentious debate in the United States during the 1980s, legislation to control adverse effects of acidic deposition through reductions in annual emissions of SO_2 and NO_x was included in the 1990 Clean Air Act Amendments, known as the Acid Deposition Control Program.[9] The acid rain program established a two-phase, market-based system to reduce SO_2 emissions from electricity-generating facilities by 10 million tons below of their 1980 levels. The objective was to achieve a 50% reduction in annual SO_2 emissions by the year 2000, when total annual emissions were to be capped at 8.9 million tons.[10] In the acid rain program, sources are issued a set number of emissions allowances annually based on their previous fossil-fuel use, and the allowances can be used in the current period, banked, or traded. All sources were required to install continuous emission monitors to measure and record emissions of SO_2, NO_x, and CO_2. Sources incur penalties if their emissions exceed their allowances during an end-of-year reconciliation. In the first phase of the program, certain high-emission plants located in eastern and midwestern states were to achieve reductions by 1995. In Phase II, which commenced on January 1, 2000, emission limits were imposed on smaller, cleaner plants and tightened on Phase I plants. The Act also called for a 2-million ton reduction in NO_x emissions by the year 2000, although NO_x emissions were not capped, nor was an emissions-trading program utilized.

The stated overall goal of the acid rain program was "to achieve significant environmental and health benefits" and the EPA has stated:

> . . . the Acid Rain Program confers significant benefits on the nation. By reducing SO_2 and NO_x, many acidified lakes and streams will significantly improve so that they can once again support fish life. Visibility will improve, allowing for increased enjoyment of scenic vistas across our country, particularly in National Parks. Stress to our forests that populate the ridges of mountains from Maine to Georgia will be reduced. Deterioration of our historic buildings and monuments will be slowed. Most importantly, reductions in SO_2 and NO_x will reduce fine particulate matter (sulfates, nitrates) and ground level ozone (smog), leading to improvements in public health". (USEPA, 2002)

The United States also signed an air quality accord with Canada in 1991 to address transboundary air quality issues. The bilateral accord formalized each country's commitment to meet their emissions targets for SO_2 and NO_x and coordinated efforts in atmospheric modeling and monitoring the effects of transboundary air pollution (USEPA, 1994). The agreement required the countries to undertake assessments of proposed actions that might cause transboundary pollution and established an Air Quality Committee to review and report progress biannually in achieving the agreement's objectives. More recently, the two countries have agreed to work on extending the 1991 agreement to cover ground-level ozone and transboundary particulate matter.

There have been no legislative changes to the Clean Air Act since 1990, but several policy initiatives concerning acid rain precursors were introduced in 2003. The first involved proposals to change the Clean Air Act by further tightening caps on SO_2 and NO_x emissions from electricity-generating facilities. The Bush administration's proposal (Clear Skies Initiative), built on the cap-and-trade approach embodied in the existing acid rain control program, would cap annual emissions of SO_2 at 4.5 million tons in 2010 and 3 million tons in 2018, and annual NO_x emissions at 2.l million tons in 2008 and 1.7 million tons in 2018.[11] The second initiative was a controversial set of proposed changes by the EPA to the New Source Review (NSR) rule. NSR (first introduced in 1977 amendments to the Clean Air Act) requires industrial facilities, including coal-fired power plants, to install pollution-control devices when they make a "significant modification" to a facility that would result in a net increase in emissions. The EPA proposed that facilities only be required to install pollution controls if the cost of their renovations is more than 20% of a generating unit's replacement cost, thus establishing a threshold for routine maintenance. The rule change, due to take effect in December 2003, was blocked by a federal appeals court as a result of a lawsuit brought by 14 states.[12] The third initiative is an EPA pro-

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[8] The annual benefits from decreased deposition in 2030 are a multiple of those in 1990 because if baseline sulphur emissions were unchanged, additional acidification would occur. All figures are in 1990 US dollars.

[9] It is noteworthy that the 1990 Clean Air Act Amendments were passed before the NAPAP assessment was complete. The role of NAPAP in the policy process is discussed below.

[10] In 2001, SO_2 emissions from utilities subject to the provisions of the acid rain program were 39% below their 1980 level and total emissions from all sources were 50% less than their 1980 level (USEPA, 2001).

[11] Actual emissions in 2000 were 11.2 million tons of SO_2 and 5.1 million tons of NO_x (USEPA, 2003). The administration proposal also capped mercury emissions, as did two other similar multi-pollutant legislative proposals under consideration. For a comparison of these proposals, see Resources for the Future (2004).

[12] The effect of the proposed rule change on emissions is unclear because NSR can create incentives to delay adoption of cleaner technologies, postpone replacement of older facilities, and discourage sources from maintaining their existing facilities, thus increasing emissions from the baseline level (Gruenspecht and Stavins, 2002). The rule change would force the EPA to drop a number of lawsuits against utilities for failing to comply with NSR requirements, thus allowing substantially more emissions than if the existing NSR requirement were met at these facilities.

posal (known as the interstate air quality rule) to achieve objectives similar to the Clear Skies Initiative through an administrative rule change applying to 29 states and the District of Columbia rather than by amending the Clean Air Act.

3.2. European policy for acid rain control

As in the United States, local health effects of air pollution were the main issue in Europe until the late 1960s, when the transboundary nature of acid rain first became evident. At the United Nations Conference on the Human Environment in Stockholm, a report was presented on the effects of long-range transport of sulphur compounds (Sweden's Case Study, 1972). In this report it was stated that:

> This continental character [of the problem caused by emission of sulfur to the atmosphere] implies, as a basis for action, that plans and programmes designed to reduce damage from acid deposition must recognize the fact that, as a rule, several states are involved . . . international agreements, legislation and control should be contemplated to cope with this problem.

Clearly, more knowledge about possible effects of acidic deposition was required before any actions would be taken. Most of the scientific research on the effects of acid rain was initially conducted in Norway and Sweden. In the same year as the Stockholm conference, a comprehensive research program—*Acid Precipitation—Effects on Forest and Fish*—was launched in Norway. The program continued until 1980 (Overrein et al., 1980). Shortly after the Stockholm conference, the Organization for Economic Cooperation and Development (OECD) launched a program to monitor long-range pollution. In 1978, the OECD monitoring network took the name *Co-operative Program for Monitoring and Evaluation of Long-range Transmission of Air Pollutants in Europe* (EMEP).

The necessity of international cooperation in dealing with acidification problems in Europe led to a ministerial-level meeting in Geneva in November 1979 within the Framework of the ECE on the Protection of the Environment. As a result, the "ECE Convention on Long-range Transboundary Air Pollution" (LRTAP) was signed by more than 30 governments, including the United States and Canada, and by the European Community.[13] The LRTAP Convention, which entered into force in 1983, was the first legally binding international agreement to deal with problems of air pollution on a broad regional basis. In addition to laying down general principles of international cooperation for air pollution abatement, the Convention established an institutional framework bringing together science and policy. It is noteworthy, however, that this agreement did not include specific requirements for emission reductions.

Increasing concern about forest damages, especially in Germany, from around 1980 provided considerable momentum for reducing air pollution, particularly sulphur emissions. In 1981 (16 November), the German journal "Der Spiegel" published a long article on forest damage from air pollutants. The cover carried the title "Es liegt was in der Luft" (There is something in the air) on a picture showing a spruce forest being suffocated by brown smoke from factories. At the bottom of the cover is the statement, "The forest is dying." The article, which created considerable stir in Germany, was strongly exaggerating the danger.[14] Some scientists (e.g., Ulrich, 1984) predicted widespread forest dieback in Europe based on evidence that, at least with hindsight, appears rather shaky. A key turning point in the international negotiations for emission reductions was the "1982 Stockholm Conference on the Acidification of the Environment," where the German delegation argued strongly for measures to control SO_2 emissions.

Several protocols involving European countries were signed later in the 1980s and 1990s. The first binding commitment on sulphur emissions came from "The 1985 Helsinki Protocol on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30%" (the 30% Club). The first protocol for the control of NO_x emissions, adopted in 1988, undertook to stabilize NO_x emissions at their 1987 level by 1994. A group of twelve countries, including Norway, decided to go a step further, signing a declaration of intent to reduce NO_x emissions by 30% by 1998 using 1986 as the base year.[15] The 1994 "Oslo Protocol on Further Reduction of Sulphur Emissions" entered into force in 1998. An effects-based approach led to a differentiation of emission reduction obligations of signatories of the protocol. The most recent agreement, the Gothenburg Protocol from 1999, deals with SO_2, NO_x, NH_3, and non-methane volatile organic compounds (NM-VOC). The goal is mitigation of problems related to acidification, eutrophication, and ground-level ozone (UN/ECE, 2000). The Gothenburg Protocol seeks to cut Europe's sulphur emissions by at least 63%, NO_x emissions by 41%, VOC emissions by 40%, and NH_3 emissions by 17% from their 1990 levels by 2010. The effects-based approach applied in the preparation of the Oslo Protocol was extended. The emission ceilings in Gothenburg were negotiated on the basis of scientific assessments of pollution effects and abatement options, including the costs of controlling emissions of the various pollutants.

In any event, electricity-generating facilities are still subject to existing emissions caps for SO_2 and NO_x.

[13] The United States and Canada have a bilateral agreement to the LRTAP convention. LRTAP is under the auspices of United Nations Economic Commission for Europe (UN-ECE).

[14] *Time* magazine had a similar article in 1985 (16 September). The cover shows a coffin with a tree inside, and the text is "Europe's Dying Forests. What is Killing all the Trees?"

[15] This turned out to be difficult. Norwegian emissions of NO_x in the late 1990s were about the same level as in 1986.

3.3. *Science and policy*

The transboundary nature of the acid rain problem complicates the policy making process because the costs of controlling air pollution are frequently borne in one jurisdiction while the benefits of reducing emissions occur in others. Perhaps because of this, there has been interest in the policy-making community on both sides of the Atlantic in conducting scientific assessments to determine the causes and magnitude of the problem before policies are enacted to control acid rain precursors.

In the United States, NAPAP was formed in 1980 to help resolve the acid rain policy debate. The purpose of the NAPAP research program was to assess what was known about the acid deposition problem and develop understanding about what might be done to resolve the problem (Russell, 1992). Acid rain was a difficult issue for two reasons: first, while acidification was thought to be a major environmental problem, scientific evidence at the time was not sufficiently compelling; second, any regulation to control acidic deposition would impose significant costs on one part of the country while other regions would receive the benefits. While the scientific research conducted under the auspices of NAPAP was widely viewed as first rate, NAPAP was not as successful in influencing policy as might have been expected, if only because interim findings were not released on a regular basis during the 10-year life of the assessment and the final assessment was printed after Congress had amended the Clean Air Act (Kraft, 1998; Russell, 1992).

In contrast, European policy formation appears to have had a strong link to the scientific community. Several research projects on the effects of acidic deposition were conducted under the auspices of the LRTAP convention (e.g., UN/ECE, 1985). The British-Scandinavian project "Surface Waters Acidification Programme" (1983–1990) is an example of successful interaction between science and policy. The program was initiated by the Royal Society and run jointly with the Royal Swedish Academy of Science and the Norwegian Academy of Science and Letters. Since the funding came from Central Electricity Generating Board and British Coal, there was initially considerable reluctance in Scandinavia about joining the project. However, there was no disagreement within the management group about the project's conclusions (Southwood, 1990), which actually were close to those of the Norwegian acid precipitation project (Overrein et al., 1980). At the conference banquet, Prime Minister Margaret Thatcher concluded her speech by saying:

> So let me confirm unequivocally tonight that the United Kingdom will meet the commitment that it has solemnly accepted to reduce acid emissions and we shall do so by embarking on a major programme of investment to protect the environment, not relying on a single method alone but combining desulphurization equipment, new gas-fired plant and other means such as the use of low-sulphur coal. Not only will our investment meet our commitment to the Large Plants Directive in full, it will also make a major contribution to reducing carbon dioxide output.

In the first years after LRTAP was established, there was interest in using cost-benefit analysis (CBA) in the policy making process in Europe (Patt, 1998). However, partly for political reasons[16] and also because of scientific uncertainties—particularly the lack of reliable relationships between deposition and environmental effects—policy makers turned increasingly to other assessment methods. Of these, the regional acidification information and simulation (RAINS) model became the most widely used assessment method in Europe. RAINS is an integrated assessment model that can be used to identify, for a given set of target deposition levels, the cost-effective allocation of measures to reduce emissions taking into account generation, atmospheric processes, environmental impacts, and control costs for SO_2, NO_x, and ammonia (Alcamo et al., 1990; IIASA, 2003).

Target deposition levels can be set on the basis of *critical loads*, another key concept used in connection with the RAINS model and the European environmental policy making process.[17] The critical load for a sensitive receptor is the highest deposition of a compound that will not cause chemical changes leading to long-term harmful effects on ecosystem structure and function (Nilsson and Grennfelt, 1988). As early as 1982, Swedish authorities mentioned critical load values for acid deposition (Swedish Ministry of Agriculture, 1982):

> A sulphate deposition of about 0.5 grams of sulphur per square meter per year could be tolerated without entailing any risk of large-scale acidification damage. If we wish to prevent the acidification of even the most susceptible lakes and watercourses, the sulphate deposition will have to be reduced to not more than 0.3 grams of sulphur per square meter per year.[18]

Critical loads can be used to map areas sensitive to acidic deposition and illustrate where deposition exceeds the levels that forests or surface waters are estimated to be able to tolerate, and have been particularly important in analyzing acidification effects on forests (e.g., Hetteling et al., 1995). Aluminum concentrations play a key role in the critical load concept. In forested regions, critical loads are based on the assumption that high aluminum concentrations (or, more specifically, a high Al/Ca ratio) in soil water are the primary cause of forest damage. However, since this assumption is

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[16] The Soviet Union opposed the use of CBA on the principle that it relied on market valuation (Patt, 1998).

[17] In fact, target deposition levels in the RAINS model are based on critical loads in receptor regions.

[18] These values were estimates of scientists (including one of the present authors, HMS) preparing for the "1982 Stockholm Conference on the Acidification of the Environment". In spite of the subjectivity, the values still seem quite reasonable.

dubious and the aluminum chemistry in soils is very complex, the critical load values for forests are very uncertain.[19]

The critical load concept and the RAINS model played important conceptual roles in European negotiations resulting in the “second generation protocols,” starting with the Oslo Protocol of 1994. By bringing scientific information about cost-effective regional abatement strategies into the negotiation process, the use of RAINS allowed emissions-reduction targets to be effects-based instead of being assigned on a flat rate or uniform basis. According to Patt (1998), some argued that the critical loads concept was politically neutral and relied only on natural science to justify targets for emission reductions. Siebenhüner (2002) considers the introduction and use of critical loads as revolutionary in terms of its impact on both the political and assessment processes of the conventions.

The RAINS model has played a critical role in the LRTAP convention because it can be used to determine the cost savings, environmental effects, and distributional outcomes of different emissions reduction scenarios and policies (e.g., Klaassen, 1996). The role of RAINS in policy development has been described in several papers (Patt, 1998; Sundqvist et al., 2002). Patt states that in view of the simplifications in the model, its extensive use is surprising. His explanation is that the simplifications increasingly were seen as necessary and that they would not bias the results towards any particular country or region. Furthermore, the policy community saw RAINS as based on impartial science.

3.4. *Economic analysis and acid rain policy*

The question of economic quantification of costs and benefits of acid rain emerged at an early stage in the debate in both Europe and the United States.[20] However, the importance of cost-benefit analysis has so far been limited due to uncertainties about acidification effects and difficulties in valuing ecosystem damages. Estimation of benefits from emissions reductions requires knowledge of the relationship between emissions, deposition rates, environmental quality, and economic welfare. While changes in deposition for different emission scenarios can be modeled with reasonable accuracy, the relationships between deposition, environmental quality and economic welfare are much more uncertain. As mentioned earlier, several models for predicting acidification of water and soil for acid deposition scenarios have been developed. However, predictions of effects on water and soil were rather uncertain, and modeling effects on forests proved to be even more difficult. Increased understanding of the acidification processes obtained through these modeling efforts has clearly had an impact on policy development. Nonetheless, there has been little direct use of results from these models in formulating acid rain policies even though the critical loads estimated by simpler models (Hetteling et al., 1995) have played a key role in Europe.

Table 1
Quantified damages across Europe from the Gothenburg Protocol pollutants in 1990 and incremental benefits in moving to the protocol ceilings scenario, in million euro, base year 1990 (Holland et al., 1999)

	Damages for protocol pollutants in 1990	Reduction in damages by moving to the protocol ceiling scenarios
Health morbidity	47000	18000
Health mortality[a]	230000	95000
Materials	1800	1200
Crops	27000	7800
Timber production[b]	2200	770
Ecological damage	Not monetized	
Visibility	Not quantified	5600

[a] The values were estimated using values of life years lost (VOLY). By using values of statistical lives, the results are considerably higher; the damage reduction becomes 160000.

[b] Only effects of ozone have been quantified.

Recently there has been greater interest in cost-benefit analysis for environmental policy making in Europe and to some extent in the United States. Although the benefit estimates are uncertain and limited in scope, the most recent cost-benefit analyses point clearly to reduced harmful health effects as the major benefit in monetary terms from further controlling acid precursors. For example, the benefits of meeting the emissions reduction targets of the 1999 Gothenburg Protocol have been quantified and monetized (Holland et al., 1999). The main results are in Table 1.

It can be seen that health effects dominate the potential benefits of meeting the Gothenburg emissions reduction targets. However, the uncertainties in the numbers are large. In a general assessment of uncertainties, Rabl and Spadaro (1999) found that the distribution in most cases is likely to be close to lognormal, implying that the lower and upper limits of a 68% confidence interval are obtained by dividing, respectively multiplying, the (geometric) mean by the standard deviation, σ_g. For chronic mortality, they estimated σ_g to be 4.

Ecological damages were not monetized in this study, but there has been a clear improvement in surface water quality (in particular, a decrease in toxic aluminum) in Scandinavia in recent years (Skjelkvale et al., 2001). Using contingent valuation methods in a study conducted in 1996, Navrud estimated a Norwegian willingness-to-pay of 80–154 million euro/year to lime surface waters in Norway to get the same increment in fish stocks as estimated for fulfillment of the Oslo Protocol (Navrud, 2002).[21]

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[19] Some scientists have been severely critical of critical load values (see e.g., Løkke et al., 1996).

[20] In fact, Robert Angus Smith may have been the first to argue that reduction of emissions in heavily polluted areas was economically justified (see e.g., *The Graphic*, 1875).

[21] The reduction in SO_2 emissions in Europe would be close to 60% in 2010 compared to 1980, which is much less than required by the Gothenburg Protocol.

The difficulties in quantifying forest damage are well illustrated in the report from the UN-EC monitoring program (UN/EC, 2002), which states:

> The results of statistical evaluations described in the present report confirm earlier findings explaining the variation of defoliation mainly in terms of the effects of weather extremes, in particular precipitation, insects, fungi and age. Also, relationships between defoliation of Scots pine and beech and sulphur deposition are substantiated by the recent statistical evaluations of the transnational data set.

Cost-benefit analysis has also been used to inform public policy in the United States.[22] A major limitation of any cost-benefit analysis of air pollution improvements is the lack of scientific data and/or uncertainty about various physical effects, particularly ecosystem effects, and the lack of data and models to value non-market effects. The most comprehensive economic assessments of acid rain control quantify health effects, some recreational fishery benefits, and visibility improvements, but do not quantify other benefits, including forest, stream, and materials damages and nonuse ecosystem values. Recent analyses of the costs and benefits of the acid rain control program indicate that health benefits—particularly the reduced risk of premature mortality through reduced exposure to sulphates—predominate, and that the benefits of the acid rain program exceed costs by a significant margin (Burtraw et al., 1997; USEPA, 1999). The costs of achieving sulphur reductions in the United States have also turned out to be considerably less than anticipated (Ellerman et al., 2000).

In addition to cost-benefit analysis, economists have used computable general equilibrium (CGE) models to analyze economy-wide macroeconomic effects of acid rain (and acid rain control policies). For environmental policy analysis, a typical CGE model, which includes modeling of the behavior of consumers and producers, factor and goods markets, macroeconomic balances, and linkages between economic sectors, is extended to include detailed treatment of the energy market and encompass externalities (e.g., valuation of environmental improvements) and pollution abatement activities.[23] CGE studies pertinent to acid rain include comparisons of traditional regulatory approaches and emissions taxes for controlling SO_2 and NO_x emissions and particulates (Conrad and Schroder, 1993); CGE models of damages from acidification of lakes and forests from emissions of SO_2, NO_x, CO_2, and particulates in Norway (Vennemo, 1997) and of the productivity effects of proposed emission reductions to curtail acidification damages in Sweden (Bergman and Hill, 2000); and a study of the national and EU-wide impacts of a tradable permit program for controlling SO_2 emissions from the electricity sector to meet the requirements of the Oslo Protocol (Conrad, 2002).

Given the complexity and uncertainties in the acidic deposition problem, CGE models are particularly useful for providing policy makers information for the design of effective environmental policies. For example, Conrad and Schroder (1993) showed that real GNP would have been higher and unemployment lower if emissions taxes had been used instead of emissions standards to control SO_2, NO_x, and particulates in Sweden. By including the detrimental effects of air pollution on production, Bergman and Hill (2000) found that the positive productivity effects of proposed emission reductions are smaller than the costs of attaining those reductions. Kiuila (2003) found that future reductions in SO_2 emissions in Poland to comply with international conventions may have a positive effect on Polish economic indicators. Edwards and Hutton (1998) linked the RAINS integrated assessment model with a CGE model of the EU to analyze the effects of carbon taxes and found that, in addition to cuts in CO_2 emissions, SO_2 emissions (and to a lesser extent, NO_x emissions) are also reduced because of the fuel savings and switching to cleaner fuels induced by the carbon tax.

3.5. Future directions

The substantial reductions in sulphur emissions in Europe and the United States show that complex environmental problems can be managed even when pollutants cross-political borders. The targets in the Gothenburg Protocol for the other pollutants may be a greater challenge, but emissions of NO_x (and probably also ammonia and non-methane volatile organic compounds) have decreased in Europe in recent years (Vestreng, 2003). Use of cost-benefit analysis to determine appropriate levels of reductions will probably increase, but not play a decisive role since uncertainties in various steps will continue to be large in the foreseeable future. Furthermore, use of cost-benefit analysis to formulate pollution control targets remains controversial. While there has been progress regarding dose–response functions for health effects of pollutants, the effects of acid deposition on forests can still not be quantified. On the other hand, use of economic models to analyze the effectiveness of various pollution control strategies is likely to increase, particularly given the success of the SO_2 emissions trading program in the United States.

Until recently, interactions of various types of air pollution were seldom considered in agreements to reduce emissions. This is unfortunate since pollution abatement measures often affect emissions of several potentially harmful compounds. Furthermore, interactions among pollutants can influence their effects. Clearly, these factors should be considered in scientific and economic assessments and in policy making. The Gothenburg Protocol was an important step towards an integrated approach to several environmen-

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[22] However, while some statutes require some government agencies to consider the benefits and costs of regulations, the EPA is expressly prohibited from considering the costs of attaining national ambient air quality standards for conventional pollutants.

[23] For a review of CGE models in environmental economics, see Conrad (2002).

tal problems. However, the agreement does not include particulates or greenhouse gases (GHGs). Several studies have concluded that measures aimed at reducing GHG emissions often have considerable co-benefits (or ancillary benefits) such as health improvements or reduced damages to materials and vegetation due to reduced emissions of particles, SO_2, and NO_x. Such co-benefits may be important in developed countries (European Environment Agency, 2003), but may play an even greater role in developing countries with large local and regional environmental problems (cf. Seip et al., 2003; Aunan et al., 2004). Co-benefits from GHG control are particularly important because they tend to accrue locally and in the near term, while benefits from reduced climate change accrue globally and over a very long time frame (Morgenstern, 2000).

4. Conclusions

There have been shifts in the main concerns driving the efforts for control of acid rain precursors in both Europe and the United States. Prior to the 1970s, health effects were the main issue. In the late 1970s, damages to soils, forests, and aquatic systems became the focus of attention. During this time, research efforts were driven by concerns about regional scale ecosystem degradation rather than health effects. Large research programs were established in the United States (and Canada) and Europe focusing on ecosystem effects. The results were clear regarding damages of acid deposition on surface waters and aquatic biota in sensitive areas, particularly in Scandinavia. The impression of dramatic forest damage in Europe created by media and some scientists in the 1980s had little basis in reality.[24] However, this led to extensive monitoring of forest health in Europe since the late 1980s, which has provided much useful information on forest ecosystems. Monitoring of forests in the United States has continued but is less systematic. Except in heavily polluted areas, the connection between acid rain precursors and/or deposition and forest health remains unclear. In the late 1990s health effects again became the dominant issue primarily due to more knowledge of harmful effects of particulates.

Estimation of economic impacts and the costs and benefits of controlling acid rain has been an issue in both Europe and the United States since the issue rose to prominence in the 1970s. However, uncertainties in the relationship between deposition and effects were so large that the role of cost-benefit analysis has been limited. In Europe, the emphasis has instead been on critical loads, a concept that, in spite of its weak scientific basis, has been received with enthusiasm by most decision makers. The RAINS model has also played an important role in deciding where emission reductions would have the largest effect in reducing the gap between present deposition and critical loads.

Recently there has been renewed interest in cost-benefit analysis to inform policy makers in Europe and to some extent in the United States. The results are partial in scope and have considerable uncertainty, but they point clearly to reductions in harmful health effects as the major benefit in monetary terms from further restrictions of SO_2 and NO_x emissions. The predicted cost savings from the use of economic incentives such as emissions trading for acid rain control has also been verified. The main concerns driving negotiations for emissions reductions at different times have not always corresponded to the most important effects in economic terms. However, recent comprehensive assessments indicate that the large reduction of sulphur emissions in both Europe and the United States have resulted in benefits that significantly outweigh the costs.

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[24] A thorough discussion of environmental policy related to “forest death” in Europe is given by Roll-Hansen (2002).

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