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ABSTRACT

This book traces centuries of human use and abuse of forest ecosystems by discussing past decades of intense burning, grazing, and timber cutting that added to the natural acidification of the soil. Air pollutants and acids generated by industrial activities worldwide are also considered. Many forests in Europe and North America now receive as much as 30 times more acidity than they would if rain or snow were falling through a pristine atmosphere; ozone levels in many rural areas of Europe and North America are now regularly in the range known to damage trees. The book is organized into six sections, an introduction and bibliography of cited references. Major topic areas discussed include: (1) signs of forest destruction worldwide; (2) pathways of pollution that in most cases are traced back to sulfur and nitrogen oxides emitted during the burning of fossil fuels; (3) economic and ecological reality of forest destruction; (4) controlling emissions through requirements for effective technology; (5) international cooperation as an essential factor in controlling a wholesale continental pollution trade; and (6) the emerging realization of the potential economic and ecological consequences of acid rain and air pollution. (BC)

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Table of Contents

Introduction	5
Signs of Destruction Unfold	7
Tracing the Pathways of Pollution	13
Counting the Costs	22
Cutting Emissions	29
Can Forests Thrive in a Commons?	36
Looking Beyond the Forest	41
Notes	45

Introduction

Three hundred million years ago, when much of Europe and North America basked in a moist tropical climate, forests of fast-growing trees spread across vast areas of swampy lowlands. Giant "scale-trees" bearing little resemblance to the trees of today stood with stately cordaites, the forerunners of modern-day conifers. After these trees died, the brackish water in which they grew protected them from decay. Time and the increased pressure of sediment helped transform the trees and surrounding vegetation into solid masses of carbon, which now comprise the extensive coal fields of the British Isles, the U.S. Appalachians, the Ruhr Basin of West Germany and Belgium, the Saar-Lorraine Basin of West Germany and France, and the Donets Basin of the Soviet Union.

5

In an odd twist of fate, humanity's use of the fossilized remains of these arboreal giants now threatens the health and productivity of their modern-day descendants. Over the past decade, scientists have amassed considerable evidence that air pollutants from the combustion of fossil fuels, both oil and coal, and the smelting of metallic ores are undermining sensitive forests and soils. Damage to trees from gaseous sulfur dioxide and ozone is well documented. Recently, acid deposition, more commonly called acid rain, has emerged as a growing threat to forests in sensitive regions. Acid deposition refers to sulfur and nitrogen oxides that are chemically transformed in the atmosphere and fall to earth as acids in rain, snow, or fog, or as dry acid-forming particles. Although acid deposition is now known to have killed fish and plants in hundreds of lakes in Scandinavia and eastern North America, its links to forest damage remain circumstantial. Yet studies of sick and dying trees in Europe and North America make the connection impossible to ignore.

Temperate forests have a long history of stress and acidification; a history that offers a critical backdrop for considering new stresses

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6

6 from air pollution and acid rain. Since the end of the last continental glaciation, 10,000-15,000 years ago, soils have slowly formed from the sterile layers of gravel, sand, and silt left behind by the retreating ice. Pioneering plants, animals, and microorganisms aided this soil development, helping form an intricate cycle of nutrient uptake and release. Death and decomposition of these inhabitants, then as now, generated acids in the soil. Where acids developed faster than other natural processes could neutralize them, the soils gradually acidified, a process that continues today.

Centuries of human use and abuse of forest ecosystems have added to this natural acidification. Many temperate forests in Europe and North America are now recovering from decades of intense burning, grazing, and timber cutting. The spruce-fir forests of New England and the Adirondacks, for example, had nearly all been clearcut for pulp by the early 1900s. Logging was often followed by burning that destroyed the forest floor. The soil formation processes taking place as these forests recover naturally increase the soil's acidity.²

Air pollutants and acids generated by industrial activities are now entering forests at an unprecedented scale and rate, greatly adding to these stresses carried over from the past. Many forests in Europe and North America now receive as much as 30 times more acidity than they would if rain and snow were falling through a pristine atmosphere. Ozone levels in many rural areas of Europe and North America are now regularly in the range known to damage trees. Despite air quality improvements made during the seventies, the average concentration of sulfur dioxide in many areas is high enough to diminish tree growth.

A comprehensive look at worldwide forest damage reveals multiple pollutants—including acid-forming sulfates and nitrates, gaseous sulfur dioxide, ozone, and heavy metals—that acting alone or together place forests under severe stress. Needles and leaves yellow and drop prematurely from branches, tree crowns progressively thin, and, ultimately, trees die. Even trees that show no visible sign of damage may be declining in growth and productivity. Moreover, acid rain's tendency to leach nutrients from sensitive soils may undermine the health and productivity of forests long into the future. Taken together, these direct and indirect effects threaten not only future wood sup-

"Waldsterben"—literally
forest death—is now
a household word in West Germany."

plies, but the integrity of whole ecosystems on which society depends.

North Americans must travel to isolated mountain peaks in the eastern United States to see the kind of massive tree disease and death now spreading throughout central Europe. The loss of West Germany's woodlands is now a potent political and emotional issue among that nation's citizenry. "Waldsterben"—literally forest death—is now a household word. A survey in the summer of 1983 showed that West Germans were more concerned about the fate of their forests than about the Pershing missiles to be placed on their land later that year.⁷ Environmental scientists in Poland and Czechoslovakia warn that forests may become wastelands if plans for increased burning of their high-sulfur coal go unchecked.

Although scientists cannot yet fully explain how this forest destruction is occurring, air pollutants and acid rain are apparently stressing sensitive forests beyond their ability to cope. Weakened by air pollutants, acidic and impoverished soils, or toxic metals, trees lose their resistance to natural events such as drought, insect attacks, and frost. In some cases the pollutants alone cause injury or growth declines. The mechanisms are complex and may take decades of additional research to fully understand. But this growing body of circumstantial evidence is one more telling sign that fossil-fuel combustion has ecological limits, and that society will pay a price for overstepping them.

Signs of Destruction Unfold

In just a few years, forest damage has spread with frightening rapidity through portions of central Europe. Trees covering between 3.5 and 4 million hectares—an area roughly half the size of Austria—now show signs of injury linked to air pollutants. (1 hectare = 2.47 acres.) No nation has better documented the destruction occurring within its borders than West Germany, where forests cover 7.4 million hectares—roughly a third of the nation's land area. Following an extensive survey in 1982, the Federal Minister of Food, Agriculture and Forestry estimated forest damage at 562,000 hectares—8 percent

Table 1: Changes in Forest Damage in West Germany, 1982 to 1983

Species	Area Showing Damage		Portion of Forest Affected	
	1982	1983	1982	1983
	(thousands of hectares)		(percent)	
Spruce	270	1,194	9	41
Fir	100	134	60	76
Pine	90	636	5	43
Beech	50	332	4	26
Oak	20	91	4	15
Others	32	158	4	17
Total	562	2,545	8	34

Source: Der Bundesminister für Ernährung, Landwirtschaft und Forsten, "Neuartige Waldschäden in der Bundesrepublik Deutschland," Bonn, October 1983.

of West Germany's forests. Just a year later, in the fall of 1983, a second survey found damage on over 2.5 million hectares, 34 percent of the nation's forests. (See Table 1.) Some of this increase resulted from a more thorough investigation the second year, but nonetheless, the damage has spread markedly. Visible injury typically takes the form of yellowing and early loss of needles, deformed shoots, deteriorating roots, a progressive thinning of tree crowns, and, in its severest stages, tree death. The symptoms appear on trees of various ages and in forests of both single and mixed species.¹

In the heavily wooded West German states of Bavaria and Baden Württemberg, home of the famed Black Forest, trees covering nearly half the forested area are damaged. Nationwide, three-quarters of the fir trees are affected, up from 60 percent a year ago. Damage to spruce, the most important species for the forest products industry, has risen from 9 percent to 41 percent, and a similar increase is evident with pine. These three conifer species, which together compose two-thirds of West Germany's forests, are the most severely struck. But damage has also been found among hardwood species such as beech and oak. Since most trees in the advanced stages of

decline are removed from the forest, more have been affected than even these alarming survey results indicate. Dr. Georg Krause of the Land Institute for Pollution Control in Essen recently stated that "hardly anyone in Germany denies the great danger to forest ecosystems."⁵

9

In neighboring Czechoslovakia, forest damage covers an estimated half million hectares. Trees on some 200,000 hectares are believed to be severely damaged, and those on 40,000 hectares in the Erz Mountains reportedly have died. Dead and dying trees are plainly visible northeast of Prague in the Krokonoše National Park, which has 34,000 hectares of forest, mostly populated with spruce. Not only are the spruce dying, they reportedly stopped regenerating in the park's mineral soils several years ago.⁶ Further north in Poland, another half million hectares of forest are affected. Forest researchers in Katowice, near Krakow, say that fir trees are dead or dying on nearly 180,000 hectares and that spruce trees in areas around Rybnik and Czeszochowa, also in the industrialized southern region, are completely gone. Environmental scientists warn that by 1990 as many as 3 million hectares of forest may be lost if Poland proceeds with its present industrialization plans calling for increased burning of the nation's high-sulfur brown coals.⁷

Accounts of forest damage in other European countries are not as well documented, but collectively they add to evidence of unprecedented forest devastation. Acute damage to pine trees was found in areas of the Netherlands in the spring of 1983, and pine and fir over a wide area in the eastern part of the country are now losing needles prematurely. Pine damage has also appeared in France and Italy. Some 12 percent of East Germany's forests are believed to be affected, and specialists in Romania have noted that 56,000 hectares of that nation's 6.3 million hectares of forests are damaged from industrial emissions. In parts of Switzerland, 25 percent of the fir trees and 10 percent of the spruce reportedly have died within the past year, and many more trees show signs of injury. Various accounts also claim that trees are suffering from air pollution in the United Kingdom, Austria, and Yugoslavia.⁸

In the late autumn of 1983, early signs of tree injury began to emerge in northern Europe. Sweden, whose dying lakes first brought inter-

national attention to acid rain, now appears to have forest damage as well. Symptoms similar to those of the declining forests of central Europe have been reported by public and private foresters primarily in the southern and western portions of the country. Spruce and pine show the most injury. Although official estimates of damage are not yet available, early reports suggest that 10 percent of the timber stock in certain regions may be affected. In southern Norway, spruce reportedly are also showing injury." A rare environmental report from the Soviet Union's Communist Party paper *Pravda* recently revealed that vast areas of forest are dying from air pollution near the automobile-manufacturing city of Togliatti, about 1,300 kilometers east of Moscow. According to the report, nearby forests along the Volga River may soon resemble a wasteland.¹⁰

Unable to attribute this massive destruction to natural events alone, scientists have turned their attention to air pollutants—an external stress that has increased greatly in recent decades. Sulfur dioxide and the acids into which it transforms have led the list of pollutant suspects. Scientists surveying West Germany's forests found that damage was greater on west-facing mountain slopes exposed to more rain and fog and thus probably to more acid deposition. The needles of ailing conifers in portions of Bavaria near the Czechoslovakian border contained more sulfur than those of healthy trees. Yet injured trees elsewhere have not shown this effect. Moreover, forests are suffering on both acidic and alkaline soils, and in areas where atmospheric concentrations of sulfur dioxide are low. Consequently, attention is increasingly being focused on the combined effects of gaseous sulfur and nitrogen oxides, heavy metals, and ozone. The debate is broadening with the apparent realization that different pollutants and mechanisms may be key factors in the damage on different sites.¹¹

Although forest destruction of the magnitude occurring in central Europe is not visible in North America, trees are suffering from air pollutants there as well. In the United States, forest damage is most evident in the Appalachian mountain ranges of the east and in the Sierra Nevada of California. Field and laboratory studies have documented not only tree disease and death, but sustained declines in growth as well. From the Appalachians of Virginia and West Virginia, northward into the Green Mountains and White Mountains of New England, red spruce is undergoing a serious dieback, a progressive

"Forests are suffering on both acidic and alkaline soils, and in areas where atmospheric concentrations of sulfur dioxide are low."

thinning from the outer tree crown inward. Damage is most severe in the high elevation forests of New York, Vermont, and New Hampshire, on peaks forested mainly with red spruce, balsam fir, and white birch. Because of high precipitation rates and the ability of conifers to intercept cloud moisture, these high mountain forests generally receive 3-4 times more acid deposition than those at lower elevations. In addition, the soils of these forests have shown a marked increase in lead concentration over the past two decades, believed to come almost entirely from the atmosphere.¹¹

11

Detailed documentation of red spruce decline has come from research on Camels Hump in the Green Mountains of Vermont. There, with the benefit of two detailed tree inventories spanning the period 1965-79, researchers have found that seedling production, tree density, and basal area have declined by about half. In 1979, over half the spruce on Camels Hump were dead. A 1982 survey of spruce throughout the Appalachians has led researchers to conclude that spruce are declining over a wide area in a variety of forests. So far, no such decline is evident in commercially valuable spruce stands found at lower elevations in northern New England and Canada. Yet in light of the large wood volume declines on Camels Hump since 1965, botanist Hubert Vogelmann of the University of Vermont warns that "if such losses in only a few years are representative of a general decline in forest productivity, the economic consequences for the lumber industry will be staggering."¹¹

As in central Europe, acid deposition has been linked to this dieback of spruce, although the evidence so far remains circumstantial. Studies on three varieties of pine in the New Jersey Pine Barrens provide the most convincing evidence to date for acid deposition's role. Analysis of tree rings shows that these pines have undergone a dramatic reduction in annual growth over the past 25 years, a pattern of decline not evident elsewhere in the 125-year tree ring record. Growth rates corresponded closely to the acidity measured in nearby streams, which in turn is a good index of the acidity of rain. With other factors such as drought, fire, insect pests, and ozone apparently not responsible, acid rain emerged as a likely cause. The researchers conclude that no other events in the trees' growth history are "as widespread, long-lasting, and severe in their effects."¹¹

12

12

Although acid deposition's link to tree injury is still debated, scientists have firmly documented tree disease and death from ozone and other pollutants in the family of "photochemical oxidants." Ozone forms from nitrogen oxides reacting with hydrocarbons (produced mainly by automobile engines) in the presence of sunlight. Its formation and concentration is often closely tied to weather patterns and geography: A highly concentrated mass of pollutants mixing under sunny conditions is a ripe setting for ozone's creation.

Ozone has killed thousands of pine trees in the San Bernardino Mountains east of Los Angeles, California, a city now infamous for its yellow-brown photochemical smog. Tree injury was evident by mid-century as air pollutants from the growing urban area were carried east by marine winds. Over the past three decades, as pollution has worsened, losses of the stately ponderosa and Jeffrey pines have increased dramatically. Researchers discovered that 4-6 percent of these trees in higher elevations died over a six-year period. Losses have been greater in the western part of the mountain range, which receives higher pollutant doses. Moreover, the growth rings in ponderosa pine cores show that annual radial growth declined 38 percent over the period 1941-1971 compared with 1910-1940, a decline attributed to the rise in air pollutants. In areas receiving the highest ozone doses, the marketable volume of 30-year-old pines declined by 83 percent. Researchers conclude in their study that "this reduction in growth, along with air pollutant caused tree mortality, combine to limit production of timber in the San Bernardino Mountains."¹⁵

Similar damage appears to be occurring in the Appalachians. Estimates now are that 4-5 percent of the eastern white pines are dying in the southern Appalachian and Blue Ridge Mountains and north into Pennsylvania and Ohio. Ozone again is the leading cause; although, both here and in the San Bernardinios, damage is exacerbated by insects attacking trees that are weakened by air pollutants. Along with tree mortality, studies of Appalachian pines have also shown substantial growth declines.¹⁶

Yellowing and early loss of needles, dieback of tree crowns, and ultimately, tree death are obvious signs that forests are suffering. Measurements of tree rings on weakened trees have shown in many cases that these visible symptoms are accompanied by substantial and

"Air pollutants may be quietly undermining the productivity of large areas of temperate forests."

sustained declines in growth. But the most disturbing of air pollution's effects on forests is that growth and productivity can be declining in trees that show no visible symptoms at all. Having documented this "hidden injury" for white pine growing in the Appalachians, researchers at the Virginia Polytechnic Institute and State University conclude that it is "highly probable that growth loss in forests subjected to low-level and long-term exposures to air pollutants may be occurring unnoticed and/or unevaluated."¹⁷

13

Tree disease and death have unfolded in central Europe and limited areas of the United States at an alarming pace, and as yet show no signs of abating. The ultimate severity and extent of this damage is a looming question. As forests not yet showing injury remain exposed to acid deposition and high pollutant concentrations for longer periods of time, the damage may well spread. Moreover, if growth declines are occurring unnoticed, air pollutants may be quietly undermining the productivity of large areas of temperate forests.

Tracing the Pathways of Pollution

Although a variety of pollutants are implicated in the forest damage and growth declines now occurring, most trace back to sulfur and nitrogen oxides emitted during the burning of fossil fuels and the smelting of metallic ores. Coal and oil contain sulfur and nitrogen that are released into the atmosphere as gaseous oxides during combustion. The quantity of pollutants emitted depends on the sulfur and nitrogen content of the fuel and, for nitrogen oxides, with the temperature and efficiency of combustion. The sulfur content of coal, for example, varies from less than 1 percent to as much as 6 percent. As a result, burning a metric ton* of coal may release 3-60 kilograms of sulfur. Smelting, a process of separating a metal from its ore, also releases large amounts of sulfur dioxide into the atmosphere when the ore contains sulfur. Common metals such as copper, nickel, lead, and zinc are smelted largely from sulfur-bearing rocks.¹⁸

Over the past century, fossil-fuel and smelting emissions have altered the chemistry of the atmosphere at an unprecedented pace. Today the

* All subsequent references to tons imply metric tons.

atmosphere receives about as much sulfur from human activities as it does naturally from oceans, swamps, and volcanoes—on the order of 75-100 million tons per year. Yet most of the emissions from human activities occur on just 5 percent of the earth's surface, primarily the industrial regions of Europe, eastern North America, and East Asia. In these areas, energy combustion and smelting add 5-20 times more sulfur to the atmosphere than comes from nature. One smelter, for example, the International Nickel Company near Sudbury, Ontario, annually emits more than twice as much sulfur as Mt. St. Helens discharged during its recent most active year of volcanic eruptions. Emissions of nitrogen compounds are harder to estimate, but those from human sources also far exceed those from natural sources in many industrial areas. In the United States, human sources are thought to account for 75-90 percent of nitrogen oxides in the air.¹⁴

Fossil-fueled power plants, industrial boilers, and nonferrous smelters lead the list of sulfur dioxide emitters. The relative contribution of these sources to total emissions can vary substantially in different countries. (See Table 2.) Electric utilities account for two-thirds of sulfur dioxide (SO₂) emissions in the United States, for example, and in West Germany, they account for over half. In contrast, Canada's electric utilities contribute only 16 percent of SO₂ emissions, while about a dozen smelters emit nearly half. Motor vehicles add little to sulfur emissions, but their internal combustion engines are the biggest source of nitrogen oxides (NO_x) in most industrial countries. In the United States, Canada, and West Germany, motor vehicles account for roughly half of total NO_x emissions, while utilities generate a third or less, and industries about a fifth. (See Table 3.)

Pollution from fossil-fuel combustion dates back well over a century to the Industrial Revolution. Coal used to heat homes and fuel factories generated a pall of smoke and haze that hung persistently over many cities in Europe and the United States. As the number of factories and homes grew, the problem worsened and many cities began to control urban smoke. But emissions of sulfur and nitrogen oxides, along with other combustion pollutants, continued to rise. Sulfur dioxide emissions began to increase rapidly in Europe after 1950 when many countries turned to high-sulfur oil. By 1970 annual SO₂ emissions had climbed to 50 million tons, two-and-a-half times mid-century levels.

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lead the list of sulfur dioxide emitters."

Table 2: Sulfur Dioxide Emissions in Selected Countries

	United States	Canada	West Germany
Quantity of Emissions*	24.1	4.77	3.54
	(million metric tons/year)		
Sources of Emissions	(percent)		
Electric Utilities	66	16	56
Industries	22	32	28
Smelters	6	45	—
Homes, Businesses	3	4	13
Transportation	3	3	3
Total	100	100	100

15

* 1980 figures for United States and Canada; 1978 for West Germany.

Sources: U.S. and Canada data from *United States-Canada Memorandum of Intent on Transboundary Air Pollution: Executive Summaries* (Ottawa, Canada: Environment Canada, 1983); West Germany data from Federal Minister of the Interior, "The Federal Government's Reply to the Interpellation of the Deputies: Air Pollution, Acid Rain and Death of Forests," Bonn, August 25, 1982, translation from the German by U.S. Congressional Research Service.

Similarly, SO₂ emissions from both the United States and Canada rose by 40 percent between the early fifties and mid-sixties.²⁰

Killer pollution episodes in Donora, Pennsylvania in 1948, London in 1952, and New York City in the early sixties drove home the hazards of polluted city air. Spurred by these threats to human health, as well as by a rising tide of environmental awareness, many countries enacted pollution control laws targeting mainly sulfur dioxide and particulate concentrations in the air. Early reductions in SO₂ emissions came primarily by switches from high-sulfur to lower-sulfur fossil fuels. In the seventies, some countries began requiring new plants to include equipment for removing sulfur dioxide from smokestack emissions. As a result, sulfur dioxide emissions in North America peaked in the mid-sixties, and since then have fallen by 14 percent in the United States to about 24 million tons per year. In Canada, sulfur

16

Table 3: Nitrogen Oxide Emissions in Selected Countries

	United States	Canada	West Germany
16 Quantity of Emissions*	19.3	1.83	3.0
	(million metric tons/year)		
Sources of Emissions	(percent)		
Transportation	44	61	45
Electric Utilities	29	13	31
Industries	22	20	19
Homes, Businesses	4	5	5
Smelters, Misc.	1	1	—
Total	100	100	100

* 1980 figures for United States and Canada; 1978 for West Germany.

Sources: See Table 2.

dioxide emissions have dropped back to mid-fifties levels of about 4.8 million tons per year. Emission levels have also stabilized or declined slightly in Europe, though trends vary from country to country.²¹

Government policies have paid far less attention to nitrogen oxides. This gas was not considered as great a health hazard, and since it was odorless it caused much less of a nuisance than sulfur with its rotten egg smell. Uncontrolled emissions from power plants and especially the burgeoning use of automobiles in the last three decades set NO_x on a rapidly rising path. Nitrogen oxide emissions are harder to estimate than sulfur dioxide since they are determined by factors other than just the nitrogen content of the fuel. But they also are thought to have risen dramatically over the last several decades, possibly doubling in Europe between the late fifties and early seventies. In West Germany, for example, NO_x emissions rose by 50 percent between 1966 and 1978. North America shows similar trends: Since the fifties nitrogen oxide emissions have roughly doubled in the United States and tripled in Canada.²²

"Recent publicity focused on acid rain has tended to ignore its common origins and interactive effects with other damaging pollutants."

Trees surrounding heavy industrial polluters, such as Canada's smelters, have suffered from pollution for some time. But the extensive forest declines now unfolding are often far from major industrial and urban centers. One consequence of the drive to purify urban air over the last couple decades has been construction of tall smokestacks to better disperse pollutants into the atmosphere. These smokestacks, along with high levels of emissions, send pollutants traveling hundreds of kilometers before returning to the earth's land and waters. The International Nickel Company's 380-meter "superstack," for example, replaced three shorter stacks in 1972. Measurements have since shown that virtually all of the sulfur and 40 percent of the heavy metals emitted travel more than 60 kilometers from the smelter.²³

17

Unlike industrial emissions of carbon dioxide, which accumulate in the atmosphere, virtually all of the sulfur and nitrogen oxides that go up eventually come down in one form or another. Some return essentially unchanged as gases. Some are deposited in dry form on surfaces such as leaves and needles, where reactions with moisture can form acids. The longer the oxides remain in the atmosphere, the more likely they are to undergo oxidation to nitric and sulfuric acid, the primary acids in acid rain. Under certain conditions, some of the nitrogen oxides will react with hydrocarbons to form ozone. Further complicating the matter, ozone can in turn speed up the transformation of sulfur and nitrogen oxides to sulfates and nitrates, the compounds in acid rain.²⁴

In light of these interactions, trying to single out one pollutant as the cause for forest damage would be difficult. Trees in a given location can be affected simultaneously by several pollutants in a variety of ways. Moreover, each pollutant may affect the formation and fate of others. If ozone helps form acid rain, trees dying primarily from acid rain are dying indirectly and in part from ozone. Recent publicity focused on acid rain has tended to ignore its common origins and interactive effects with these other damaging pollutants. Divorcing acid rain from the complete pollution picture in this way may lead to ineffective strategies to control it, and more importantly, may prevent other damaging pollutants, such as ozone, from getting the attention they deserve. Nonetheless, acid deposition is of special concern be-

18

cause of its pervasiveness, its insidious ways of inflicting damage, and its potential long-term consequences.

18 Although acid rain was recognized over a century ago, only in the last three decades has the phenomenon become widespread. In broad areas of eastern North America and northern and central Europe, the annual pH of rain and snow now averages between 4 and 4.5. The pH scale, commonly used to express acidity, ranges from 0 to 14, with anything less than 7 considered acidic. The scale is logarithmic; a decrease of one unit means a 10-fold increase in acidity. (Vinegar, with a pH of about 3, for example, is 100,000 times more acidic than baking soda, with a pH of 8.) Rain falling in preindustrial times is thought to have been in the range of 5.6, slightly acidic from interactions with natural carbon dioxide in the atmosphere. Precipitation in many industrial regions is now 10-30 times more acidic than would be expected in an atmosphere free of humanity's pollution.²⁵

The precise mechanism by which acid deposition may be damaging forests is not known. Sulfates and nitrates raining down as acids have drastically different effects on different forest stands, and even on different tree species in the same forest stand. Incoming acids affect interactions between the soil and living biomass of an ecosystem in complex and varying ways. Soil structure and composition, vegetation type, climate, and elevation are only some of the natural determining variables. Yet research over the last decade has uncovered some common effects of acidity that point to several pathways by which acid deposition can threaten forests:

Trees derive their nutrition primarily from elements such as calcium, magnesium, and potassium that are weathered from minerals in the soil. Acid deposition adds hydrogen ions to the soil, which displace these important nutrients from their sites bound to soil particles. Soils with a pH of 5 or more are seldom in danger since they have plentiful calcium carbonate (the constituents of lime) or silicates (which have abundant calcium, potassium, and/or magnesium) that effectively neutralize the acid ions. Yet soils at lower pH levels have fewer of these buffering agents. Competition from incoming acids causes the leaching of calcium and magnesium from the soil. Large areas of the southeastern United States, the Appalachian, Adirondack, and New

"Precipitation in many industrial regions is now 10-30 times more acidic than would be expected in an atmosphere free of humanity's pollution."

England mountain ranges, the Canadian shield of eastern Canada, and extensive areas in Scandinavia, for example, are underlain by slightly acidic, poorly buffered soils that are especially susceptible to this effect. Although soil changes generally take place over a long period of time, soil studies in Sweden suggest that substantial leaching of nutrients from sensitive soils can occur in just a decade.²⁶

19

Sulfates and nitrates, the other key constituents of acid deposition along with hydrogen ions, can initially have a fertilizing effect on many soils and for a time may actually boost tree growth. Forests in Scandinavia and portions of West Germany seem to have shown this effect. Yet this enhanced growth is short-lived, for eventually these "fertilizer" supplies will exceed the forests' capacity to use them. Sulfate saturation usually precedes nitrate saturation, but excess quantities of either or both simply pass through the soil, carrying vital nutrients with them. With forest productivity closely tied to nutrient availability, this leaching of soils by hydrogen, sulfate, or nitrate ions eventually reduces forest growth.²⁷

Research also has shown that heavy metals—either mobilized in the soil or introduced from the atmosphere—may be involved in the forest damage now occurring. Dr. Bernhard Ulrich, a soil scientist who has studied damaged beech and spruce forests in the Solling Plateau of West Germany for nearly two decades, has hypothesized that as soils become increasingly acidic, aluminum, which is normally harmlessly bound in soil minerals, becomes soluble and toxic. The free aluminum attacks the tree's root system, making the tree less able to take up moisture and nutrients and to protect itself from insect attacks and droughts.²⁸

Trace amounts of heavy metals can also enter the forest from the atmosphere. Combustion of fossil fuels, smelting, the burning of leaded gasoline, and refuse incineration are major sources of trace metals in the air. Field and laboratory research at the University of Vermont suggest that heavy metals and acid deposition act synergistically on forest systems, stunting the growth not only of trees, but of mosses, algae, nitrogen-fixing bacteria, and fungi that are essential to a forest's health. Between 1965 and 1980, metal concentrations have markedly increased in the soils on Camels Hump, a site of massive spruce dieback in Vermont's Green Mountains. Lead con-

centration doubled, while that of copper rose by 40 percent and zinc by 70 percent. These metals enter the forest with the rain and fog, which in the Vermont mountain peaks have average acidities 100 times greater than "pure" rain.²⁹ Researchers at the Oak Ridge National Laboratory in Tennessee have analyzed tree cores and found higher metal concentrations in recently-formed wood. Cores taken from southern Appalachian trees showed concentrations of zinc, copper, chromium, and aluminum generally high enough to be toxic.³⁰

Of all the pathways by which air pollutants can affect forests, changes in the soil—whether by nutrient leaching, accumulation of heavy metals, or mobilization of toxic aluminum—are the most foreboding. In sensitive ecosystems these changes may be irreversible, thus harming not only mature trees now standing, but the seeds and seedlings that will become the forests of the next generation. The beech trees studied by Dr. Ulrich in West Germany have great difficulty regenerating, apparently because of acidity in the upper soil layers. The number of spruce and maple seedlings on Camels Hump in Vermont has declined by about half over the last two decades, and the number of spruce seedlings in the higher elevations of New York's Whiteface Mountain has dropped by 80 percent.³¹

Sulfur and nitrogen oxide gases can also enter trees directly through their leaves or needles, much as carbon dioxide is taken in for photosynthesis. These pollutants can alter the trees' metabolism and ability to produce food, and thus its productivity and growth. Forestry experts at the 1982 Stockholm Conference on Acidification of the Environment reported that tree growth can apparently decline when average yearly sulfur dioxide concentrations run as low as 25-50 micrograms per cubic meter, levels that prevail over large portions of Europe.³² For comparison, the national annual ambient air quality standard for sulfur dioxide in the United States is 80 micrograms per cubic meter, and the European Economic Community standard is 80-120. Thus, air quality levels established to protect human health appear too lenient to protect the health of forests.

Dry sulfate and nitrate particles deposited on moist foliage can form acids that leach nutrients from leaves and needles much as they are leached from soils. West German scientists have found magnesium

"Air quality levels established to protect human health appear too lenient to protect the health of forests."

and calcium deficiencies in the needles of declining spruce trees in the Black Forest and Bavarian Forest of southern West Germany. They suggest that acid deposition, aided by ozone that first attacks the needle's outer surface, is weakening trees through the foliage as well as the soil.³³

21

Ozone by itself has been found to damage trees when concentrations of 100-200 micrograms per cubic meter last 6-8 hours a day for several days. This is roughly 2-3 times greater than natural background levels typical for a summer day. In many rural areas of Europe, average daily concentrations are regularly in this range, and peak levels can exceed natural levels by 6-10 times. (See Table 4.) Acute stress from these episodic peaks may worsen damage caused by high average concentrations. Some scientists studying the pattern of spruce and fir dieback in the Black Forest and the state of North Rhine Westfalia contend that ozone is the leading cause there.³⁴

No single hypothesis can account for the varying patterns of forest destruction observed. A reasonable explanation for the decline on one site may appear infeasible for another. While these complexities frustrate the search for a clear-cut cause and effect, they are not surprising. Apart from their unique pathways of destruction, air pollutants are most simply understood as a biological stress. Just as stress is manifest in human beings in different ways—such as ulcers or high blood pressure—air pollution stress on trees shows up in a variety of ways depending upon the tree species, soil type, and the specific pollutants involved. Pollution-induced stress weakens a biological system and makes it more susceptible to harm from natural stresses such as droughts, insect attacks, frost, and wind. In the Appalachians, strong evidence exists that the growth of trees has become more closely tied to temperature and rainfall over the past few decades; a sign of increased stress.³⁵ Droughts may have triggered the fir dieback in West Germany in 1976 and the spruce decline on Camel's Hump in the mid-sixties. Insect infestations and root fungi have been linked to forest damage in the United States and Europe. Yet these natural factors alone seem insufficient to explain the sustained patterns of dieback and decline. Whether as a predisposing stress or a primary cause, air pollutants appear to figure prominently.

22

Table 4: Summer Ozone Concentrations in Selected European Countries

	Upper Daily Average	Peak	Increase of Daily Average Over "Natural" Levels ¹
	(micrograms per cubic meter)		(percent)
Netherlands	80-130	500	189
West Germany ²	100-150	400-500	200
United Kingdom	90-165	200-500	210
Belgium	—	300	—
France	70-120	—	160
Norway	—	200-300	—

¹ The midpoint of the upper daily average range is used for this calculation; "natural" ozone concentration assumed to be 60 micrograms per cubic meter.

² Daily average figures for West Germany are from the Black Forest; the peak values are frequently recorded in rural areas. Peaks in Black Forest typically are 110-180 micrograms per cubic meter.

Source: Environmental Resources Limited, *Acid Rain: A Review of the Phenomenon in the EEC and Europe* (London: Graham & Trotman Limited, 1983).

Counting the Costs

West Germany's spruce and fir forests are typically managed in even-aged stands with trees harvested at 80-130 years of age. Although damage first appeared on older trees, spruce and fir of all ages are now affected. Foresters expect the death of the younger trees to significantly disrupt the wood market. In the summer of 1983, when forest damage was still placed at 8 percent, the reported value of the trees that had been lost was about \$1.2 billion. Spread equally over a ten-year period, these losses translate into about a 5 percent decline in annual timber production, worth about \$200 million per year.³ With damage now covering a third of West Germany's forests, the value of this annual timber loss is bound to rise. A growing portion of the

"In the summer of 1983, the reported value of the trees that had been lost in West Germany was about \$1.2 billion."

planned annual harvest consists of dying trees removed from the forest. Over the next few years, the harvest may reach three times the normal level, and the dumping of valuable wood on the market will undoubtedly depress timber prices. Even under the optimistic assumption that the ongoing destruction ceases and that the damaged forests can be restored, future wood harvests will likely be reduced as a result of the present overcutting. Dr. H. Steinlin, Director of the Institut für Landespflege at Albert-Ludwigs University in Freiburg, expects that from the late nineties into the first quarter of the next century, West Germany will be less self-sufficient in timber.¹⁷

23

The economic and ecological reality of this forest death has led West German forest researchers to visualize a very different forest of the future and to begin planning alternative management strategies. In Bavaria and other severely damaged areas, soils are being limed in an attempt to counteract acidity. But without plowing lime into the soil—a prohibitively expensive task for such large areas—mineral soils cannot be restored beyond the surface, and this strategy, therefore, is not an ultimate solution. Moreover, liming does nothing to reduce stress caused by ozone and gaseous sulfur dioxide. According to a recent *Journal of Forestry* editorial, jointly written by a German professor of forest policy, the president of the German Forestry Association, a Regensburg forester, and a former U. S. Fulbright Visitor to Germany, "Air pollution is now the problem that concerns West German foresters most. The results of 200 years of forest management seem to be extinguishable within the next 10 years . . . Only a few people think about an all-too-possible scenario: central Europe without forests."¹⁸

Many of Europe's forests are intensively managed conifer stands that yield large timber volumes from a comparatively small area. With only one-fifth the forested area of North America, the countries of Western Europe harvest about half as much wood as Canada and the United States combined. Western Europe accounts for 15 percent of the world's industrial wood harvests, even though it has only 4 percent of the world's forests.¹⁹ As with agricultural crop production, the economic gains of intensive forestry are made at the risk of greater vulnerability to outside stresses; a vulnerability obviously compounded if the species being grown is sensitive to the stress. Since planted trees are purposely managed and valued for timber produc-

24

tion, damage to them results in a direct economic loss. Though West Germany's situation is in some ways unique, plantation forestry and more intensive forest management are becoming more common worldwide, increasing both the likelihood and potential economic effects of forest damage.

More than half the sawtimber in the United States comes from the harvests of just a few species, notably Douglas fir and ponderosa pine in the West, and loblolly, longleaf, shortleaf, and slash pines in the South. Between the mid-sixties and the late seventies, the forest industry increased its annual planting and direct-seeding of commercial species 2.5 times. Total U.S. plantings in 1978 were over 800,000 hectares, a substantially greater area than is annually planted for industrial wood in all of the tropics. Roughly 85 percent of the U.S. softwood timber harvest comes from the South and the Pacific coast area, yet because Pacific forest industry lands cannot sustain current harvest levels, the U.S. Forest Service projects no increases in softwood supplies there until well into the next century. In contrast, supplies from the South are expected to rise by nearly 50 percent by 2030, and timber companies increasingly are turning to the South's favorable growing conditions.¹¹

Many of the pine species currently being planted in the South and Southeast are among those that have shown damage or growth declines from ozone and possibly acid deposition. Although the evidence so far is too weak to project future economic losses, some southeastern forest lands may produce less than optimum yields. Roughly 10 percent of the annual forest growth in the eastern United States occurs in areas of high sulfate deposition—over 40 kilograms per hectare annually. Over 75 percent occurs in areas receiving annual sulfate doses of 20-40 kilograms per hectare.¹¹ Soils in many parts of the Southeast are susceptible to acidification, and acid deposition may in time reduce soil fertility to the point that tree productivity begins to decline. According to one 1983 study examining the economic effects of acid rain, a 5 percent growth decline in southern softwoods would translate into an annual loss of timber sufficient for about one-tenth of the new U. S. homes built each year.¹² Scientists have noted the "urgent" need to test managed forest species for sensitivity to both nitric and sulfuric acids, and that such tests must allow enough time

to measure effects that appear only after several years or decades of exposure.¹¹

While clearly concerned, the U. S. forest products industry maintains that the evidence linking forest damage with acid deposition is not sufficiently convincing to warrant action. Surveys of the largest forestry companies have yielded no clear sign that declines in forest productivity from acid deposition have occurred on their lands. The forest products industry, however, is threatened not only with potential timber losses caused by acid rain but by regulations that might be issued to control pollution emissions. Producing paper and other forest products consumes large amounts of energy, and additional pollution controls for power and manufacturing plants would raise production costs. The industry, therefore, does not now support costly acid rain control measures, which it feels cannot guarantee an efficient solution to a known problem. Moreover, commercial timber lands are visibly suffering from infestations of spruce budworm, pine beetles, and gypsy moths—problems of more immediate concern to most timber companies than acid deposition.¹² Yet if the industry became convinced that acid rain was causing even relatively small declines in forest productivity, this position probably would change. Dr. Ely Gonick, senior vice-president of International Paper, the nation's largest private forest land holder, points out that paper mills are highly capital intensive and thus are "captives of their geography. They depend on a very long and continuing supply of reasonable cost wood to survive economically. If acid rain damaged that supply, then the mills could fail and jobs would be lost."¹³

25

In Canada, damage to vegetation surrounding sulfur-emitting smelters has long been evident, but so far no firm evidence exists of growth declines from regional air pollution or acid deposition. Yet more than half of Canada's productive forest lies in the eastern part of the country where precipitation is acidic and soils have little buffering capacity. With one out of every ten Canadian jobs dependent on the forest industry, and annual forest products valued at more than \$20 billion dollars, Canadian officials are understandably concerned about acid deposition's potential to damage their timber supply. According to Dr. Raymond Brouzes of Environment Canada, "A reduction in tree productivity as small as 1 percent or even .25 percent per

26

year would result in a significant reduction in total wood production if compounded over the life-span of a tree. Such a reduction could have serious implications on the fibre supply and economic well-being of the forest-based industries." Regarding the threat to Canada's forests, Dr. F. H. Bormann of Yale University adds, "The danger is that by the time a 15 to 20 percent loss in productivity has been documented degradation will be irreversible."

Canada already faces severe consequences from former neglect of its forests. Poor management practices and inattention to regeneration have left Canada's timber lands in a sorry state. Hoping to ease this trend, the provinces of Ontario and New Brunswick have established tenure agreements with private forestry companies, encouraging them to invest in public forest land and thereby increase timber supplies and future yields. According to Dr. H. Krause, forest resources professor at the University of New Brunswick, improved management practices in New Brunswick are projected to eventually more than double the province's yearly average incremental timber growth. Yet Dr. Krause follows with an as yet unanswerable query: "Will this increased management input be counteracted, in the future, by continuing acidic deposition?"¹⁸

Although acid rain tends to be associated with the industrial world, it has now been measured in many developing countries as well. Large portions of Brazil, southern India, Southeast Asia, and eastern China are underlain by the type of soils most susceptible to acidification. Threatening levels of soil acidity have reportedly been measured in some of these areas. Trees are being planted in these and other developing regions to meet not only growing industrial wood demands, but critical needs for fuelwood and charcoal. The ambitious industrialization goals set by many of these countries—in which fossil fuels typically figure prominently—raise the possibility of acid deposition eventually countering some of the gains made from plantation forestry.

One special concern for Third World plantation forestry is the potential for acid rain to inhibit the functioning of soil microorganisms. These minute creatures appear to play key roles in successfully establishing tree plantations on degraded lands, where much Third World tree planting is taking place. Nitrogen-fixing bacteria, for example, are

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behind the hardiness and partial nutrient self-sufficiency of legumes, a family of trees increasingly chosen for fuelwood plantations. These bacteria and other important microorganisms may not function as well under the altered soil conditions brought about by acidification. Devoting large areas to monoculture plantations of fast-growing trees appears necessary to lessen the Third World's growing fuelwood crisis. Yet unless soils are protected from increased acidification, vital wood supplies may diminish."

27

In addition to this worldwide growth in plantations, attempts to profitably increase short-term wood production are leading to greater use of intensive harvesting practices that may cause long-term declines in forest productivity. Researchers at the Hubbard Brook experimental forest in the White Mountains of New Hampshire found that losses of calcium, potassium, and nitrogen during the ten years following an experimental clearcut of their hardwood forest were, respectively, over 3, 7, and 11 times greater than from an adjacent uncut forest. For calcium and potassium, these losses were over half the amount stored in the forest ecosystem.²² Clearcutting is often combined with whole-tree harvesting, in which the branches, leaves, and twigs are removed from the forest along with the trunks. Leaves and twigs are especially rich in nutrients, which, if left in the forest, would return to the soil as the biomass decomposed. Clearcutting combined with whole-tree harvesting may export 2-3 times more nutrients from the forest than a clearcut where only the trunks are removed.²³

The Hubbard Brook researchers point out that it might take 60-80 years for their experimental hardwood forest, from which no wood was removed following the clearcut, to return to precutting conditions. Cutting again before full nutrient recovery would likely degrade the forest's productivity over time. Whole-tree harvesting no doubt would postpone recovery even further, as would acid deposition, which by itself can increase the rate of nutrient leaching three-fold in some poorly-buffered, acidic soils. Few studies, if any, have examined the effects of acid deposition combined with these intensive forestry practices. Yet taken together, they increase the likelihood of long-term declines in forest productivity. Scientists reporting at the 1982 Stockholm conference on acidification note that "in areas of intense acidic deposition these (nutrient) losses added to those associated with logging, particularly whole-tree harvesting, may jeopardize

28

the ability to sustain yields."⁵⁴ Dr. Gilles Robitaille of Canada's Laurentian Forest Research Centre emphatically echoes this concern: "We strip cut, cut by diameter and clear-cut . . . We recover the trunks, branches, foliage, needles—everything. Nothing is left on the ground to break down and improve soil quality. Along comes the acid rain which leaches the remaining nutrients from the soil. What is left to regenerate the forest?"⁵⁵

Growth declines and tree damage on forest lands intensively managed for marketable timber will result in direct economic losses. Yet the changing ecology of the natural forest system brought about by acid deposition and air pollution may have severe consequences as well. From an ecological point of view, acid deposition and pollutants are relatively new stresses, and knowledge of complex forest systems is too limited to predict how forests ultimately will respond to them. While acknowledging this difficulty, scientists with the Norwegian Interdisciplinary Research Programme on acid precipitation conclude after eight years of study that in susceptible areas the issue seems to be "a question of proportion and time required rather than whether any ecological effects appear or not."⁵⁶

The industrial world's forests are now subjects of an ecological experiment of unprecedented scale and untestable outcome. Where pollutants remain at relatively low levels, many forest systems will continue to absorb them without major damage to the soil, microorganisms, or trees. Yet as chronic stress increases, ecological theory predicts a staged decline that in extreme cases could end in complete ecosystem collapse.⁵⁷ This has occurred around high emission sources such as the smelters at Sudbury, Ontario, and Copperhill, Tennessee. The forest decline spreading in central Europe could be the beginning of such a complete collapse on a much broader scale. Even if pollution remained at today's levels, forests and soils continually exposed to this degree of stress may in time lose their resistance. Moreover, long before the ecosystem ceases to function, other resources that depend on a well-functioning forest will be affected. Forest effects do not stop at the forest boundary, but ripple to groundwater, streams, and lakes which receive acids and metals that break from the forest cycle. Humanity's intimate connections to these

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forest systems ensures that it will not escape feeling the effects of their demise.

Cutting Emissions

29

Coal is much more abundant than oil and will be the primary polluting fossil fuel in the decades ahead. About 660 billion tons are now technically and economically recoverable, which at today's rates of production would last well over two centuries, compared with roughly four decades for oil. Moreover, some 10 trillion tons of coal—equal to more than 800 times the world's annual use of energy—are known to exist and may ultimately be recovered.⁵⁶ Thus, no apparent resource constraints will by themselves limit emissions of sulfur and nitrogen oxides in the foreseeable future. Emission levels will depend on such factors as the rate of economic growth, energy prices, the competitiveness of alternative energy sources, automobile use, and, of course, pollution control measures—all factors subject to much uncertainty. Yet existing trends suggest that atmospheric pollutants and the acidity of precipitation will increase in much of the industrial and developing world.

Sulfur dioxide emissions in North America and the ten-member European Economic Community (EEC, also known as the Common Market) will remain at their existing high levels, but probably will not greatly increase. (See Table 5.) In the EEC, declining use of fuel oil (with an average sulfur content of 2.5 percent) and rising use of coal (with an average sulfur content of 1.5 percent) has the net effect of maintaining SO₂ emissions at roughly current levels. In addition, requirements in the Netherlands and West Germany that new coal-fired power plants be equipped to desulfurize flue gases also help keep EEC emissions from rising. In North America, pollution controls on new power plants and only modest emissions increases from Canada's smelters keep sulfur dioxide emissions from rising substantially. But in the countries of eastern Europe, already among the most heavily polluted in the world, increased burning of high-sulfur coal and lignite is projected to increase SO₂ emissions by 36 percent. By the year 2000, emissions from this region are expected to be double those in the United States, even though it is one-seventh as large in

area. Emissions from the Soviet Union, which are now about equal to those of the United States, are also expected to increase by a third.

Table 5: Projected Changes in Sulfur and Nitrogen Oxide Emissions, 1980-2000

	Sulfur Dioxide			Nitrogen Oxides		
	1980	2000	Change	1980	2000	Change
	(million metric tons)	(million metric tons)	(percent)	(million metric tons)	(million metric tons)	(percent)
United States	24.1	26.6	+10	19.3	24.1	+25
Canada	4.8	4.5	-5	1.8	2.4	+33
EEC	18.6	19.0	+2 ^a	9.2	11.1	+21
Soviet Union*	25.5	34.6	+36	—	—	—
Eastern Europe*	40.7	55.3	+36	—	—	—

* Year 1982 and 2002 estimates rather than 1980 and 2000. Estimates for nitrogen oxide emissions not available or reliably estimated.

Sources: U.S. and Canada: *United States-Canada Memorandum of Intent on Transboundary Air Pollution: Executive Summaries* (Ottawa, Canada: Environment Canada, 1983); EEC: Environmental Resources Limited, *Acid Rain: A Review of the Phenomenon in the EEC and Europe* (London: Graham & Trotman Limited, 1983); (2.5 percent growth scenario); Soviet Union and Eastern Europe: N.H. High-ton and M.J. Chadwick, "The Effects of Changing Patterns of Energy Use on Sulfur Emissions and Depositions in Europe," *Ambio*, Vol. 11, No. 6, 1982.

In contrast to the varying projections for sulfur dioxide emissions, nitrogen oxides are on the rise nearly everywhere. In the countries of the EEC, where NO_x emissions are thought to have increased 40-50 percent since the early seventies, emissions are projected to climb another 5-21 percent before the century is out. (The range reflects different assumptions for the rate of economic growth.) This expected rise is mainly attributed to utilities burning less oil and more coal,

since coal combustion generates more nitrogen oxides than an equivalent amount of oil combustion, and to the expected increase in cars traveling the EEC highways. In the absence of additional controls in the United States, nitrogen oxide emissions from utilities are projected to increase 55 percent. This estimate assumes a higher growth in energy demand than now seems likely, thus actual NO_x increases will probably be somewhat lower than the 25 percent total rise projected by the joint U.S.-Canadian work groups. Canada's biggest increase will come from vehicles, whose emissions are projected to rise by 50 percent to roughly 1.7 million tons, or over 70 percent of total NO_x emissions.

31

In most areas where acid rain is now a problem, sulfur dioxide is responsible for about 70 percent of the acidity and nitrogen oxides for about 30 percent. (There are notable exceptions, such as areas in the Pacific and Rocky Mountain regions of the United States, where nitrogen oxides contribute a much greater share to precipitation acidity.)³⁰ But the rapidly rising emissions of NO_x and steady or declining emissions of SO₂ suggest that in many areas, nitrogen oxides will play an increasingly important role in the creation of acid rain over time. Moreover, since chemical reactions involving NO_x lead to ozone, ozone levels in areas conducive to its formation will increase as well. Given ozone's known toxicity to plants and trees, along with evidence that ozone helps form acid deposition and may make trees more susceptible to acid deposition's effects, reducing nitrogen oxides should clearly be part of any control strategy to protect forests.

Although estimates of future emissions in Third World countries are not readily available, trends suggest that air pollution and acid rain will worsen in many of them over the coming decades. Precipitation acidity is not widely monitored in developing countries, but rain with a pH of 4.5 or below has been measured in cities in China and India.³¹ Industrialization plans for many of the most populous Third World countries call for vast increases in coal burning, following essentially the same path taken by today's industrialized countries early in the century. China's annual coal output, for example, increased more than 20 times between 1949 and 1982, and is now up to 666 million tons, almost as much as output in the United States. If China's plans to increase per capita energy consumption are fulfilled, the nation will be burning some 900 million tons of coal each year by the turn of the

32

century.⁶¹ Brazil's consumption of coal has been rising at an average rate of about 10 percent per year, and steel, cement, and paper companies are switching from oil to coal.⁶² India plans to increase coal production to 325 million tons by 1995, roughly 2.6 times greater than 1982 levels. Sulfur dioxide emissions from coal and oil have nearly tripled in India since the early sixties, and were estimated at 3.2 million tons in 1979—slightly less than current emissions from West Germany. Dr. C.K. Varshney of Jawaharlal Nehru University's School of Environmental Sciences sees problems from acid rain as "very much in the making in the country . . . The current pace of development is bound to promote acidification of the environment."⁶³

High levels of ozone and other gaseous pollutants are already problems in some developing countries. Urban areas situated in valleys surrounded by mountains, such as Mexico City, Guatemala City, and Caracas, are becoming heavily polluted from automobile emissions. Trees are dying along heavily traveled corridors in Mexico City, and uncontrolled burning of leaded gasoline is of increasing concern in Guatemala City and Malaysia. In some of these regions, governments are encouraging polluting industries to move to outlying areas or to build higher smokestacks, precisely the strategies believed to have worsened acid rain in the rural areas of industrial countries.⁶⁴

Without efforts to brake these rising emissions, destruction caused by acid rain and air pollution two decades from now may dwarf that evident today. Government policies must begin to recognize that damage to forests, soils, and lakes is an added cost of fossil-fuel combustion that is not now taken into account in the prices consumers pay. Society is in effect subsidizing fossil-fuel generated electricity, motor vehicle use, and metals production by allowing free use of the environment to absorb the resulting pollution. Such an "externality," so called because the social costs are external to the private costs, means a portion of the real cost of these activities is hidden. Since costs appear lower than they really are, more of these activities take place than is optimum for society. Where the environment can no longer assimilate combustion's pollution, these external costs are now becoming visible in the form of acidifying lakes and dying forests.

Correcting this inherent market failure requires that those fostering the pollution begin paying for it—either through technological con-

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now require power plants to control
sulfur dioxide emissions with effective technologies."**

trols, emissions taxes, sales taxes (for example on motor vehicles), or other means. National energy and environmental strategies are not yet doing this, and they are inadequate to prevent air pollution and acid deposition impacts from worsening in the future. Only a handful of countries now require power plants to control sulfur dioxide emissions with effective technologies. The majority still rely on low-sulfur fuels and dispersion through tall smokestacks to control pollution. The former will prove inadequate for the long term, and the latter only transfers a portion of the pollution damage from urban to rural areas.

33

The United States, West Germany, and the Netherlands stand out as having taken some serious action in recent years. New power plants in these countries are required to install flue gas desulfurization (FGD) equipment, often called "scrubbers," which is the most widely used technology for reducing sulfur dioxide. FGD reduces SO_2 emissions by 80-95 percent, and typically adds 10-15 percent to electricity generating costs. Because of slower energy growth and high interest rates, comparatively few new power plants will be built over the next decade or two. Achieving substantial pollution reductions in the near term will thus require that existing plants be controlled. Only West Germany has begun to tackle this politically difficult and more expensive task. With heightened concern over spreading damage to the nation's forests, the West German Bundestag passed legislation in July of 1983 calling for tight controls on the largest 150 of its 1500 existing plants, those over 300 megawatts.⁶³ Although the U.S. Congress has before it some dozen proposals to curb emissions from existing sources, political divisions over the regional distribution of costs and benefits from such measures have so far prevented their passage.

Efforts to control nitrogen oxide emissions also have far to go if existing levels are even to be capped, no less reduced. Nitrogen oxides are harder to control than sulfur dioxides since they result not only from nitrogen contained in fuel, but from the oxidation of nitrogen present in the air. Both utilities and industries could reduce NO_x emissions up to 50 percent with combustion modifications costing roughly 1 percent of electricity generating costs. Yet so far little attention has been given to even these modest controls. More stringent controls would require technologies such as selective catalytic reduction (SCR) that treat flue gases for nitrogen oxides as scrubbers do for

34

sulfur dioxides. These systems can reduce NO_x by 90 percent and typically cost 5-8 percent of generating costs, roughly half as much as scrubbers."

- 34** Japan stands alone in requiring that power plants substantially reduce nitrogen oxides along with sulfur dioxide, primarily a response to the nation's health-threatening urban smog problems. To meet the required 73 percent NO_x reduction, Japanese power plants typically must go beyond combustion modifications and apply selective catalytic reduction, which has barely been tried in other countries. Equipment to desulfurize flue gases has been installed in over a thousand Japanese plants of various sizes and types—utilities, industries, and smelters—compared with at most 200 in the United States. Moreover, the Japanese plants use a regenerative system that yields marketable byproducts—elemental sulfur, sulfuric acid, or gypsum—rather than the hundreds of thousands of tons of wet sludge produced annually from the "throwaway" desulfurization process used in most U.S. plants. A ready market for sulfur materials initially made this option especially attractive, and with land for waste disposal extremely scarce, the cost of sulfur recycling was factored into electricity costs. Indeed, pollution control accounts for roughly 25 percent of the total cost of coal-generated power, and Japan's electricity costs are among the highest in the world. Yet Japan appears willing to foot this bill for the benefits of improved air quality. Writes Dr. Jumpei Ando of Chuo University, "From high buildings in Tokyo one can now see Mt. Fuji 100 kilometers away."

Some promising pollution control technologies are now on the horizon, which will expand options for controlling emissions from both new and existing plants. Besides improvements in flue gas desulfurization, two technologies that control both sulfur and nitrogen oxides during combustion look attractive. Fluidized bed combustion (FBC) involves burning crushed coal on a bed of limestone suspended by an upward injection of air. The limestone reacts with the sulfur dioxide as the coal burns, reducing SO₂ emissions by 90 percent or more. As with scrubbers, the resulting wastes must either be disposed of or made into marketable sulfur products. Because combustion is carried out at a lower temperature, nitrogen oxide emissions are 15-35 percent lower than from a conventional boiler. FBC is now being tried at some 30-40 plants in West Germany, the United King-

"Some promising pollution control technologies are now on the horizon."

dom, Sweden, the Netherlands, and the United States. Most plants currently using FBC have capacities of less than 40 megawatts (many are under 5 megawatts), but several in West Germany have capacities of 100 megawatts or more. Sweden's success with the technology at a 15-megawatt plant has led it to consider building a 330-megawatt commercial-scale combustor. In the United States, a fluidized bed boiler is being tested under the direction of the Electric Power Research Institute at a plant in Kentucky. A larger demonstration project is expected to follow this 20-megawatt pilot-scale plant.⁶⁸

35

Another promising technology—the limestone injection multistage burner (LIMB)—appears to deserve a rapid thrust forward. It combines combustion modifications for NO_x control with injection of limestone into the combustion chamber for control of SO₂. LIMB's main advantage lies in retrofitting: For a capital cost just over one-tenth that of scrubbers, LIMB can apparently remove 50-70 percent of both sulfur *and* nitrogen oxides from existing plants. The technology is still being developed, but pilot-scale tests make it look promising.⁶⁹

Motor vehicles are the leading source of nitrogen oxide emissions in most industrial countries. They are also a leading source of hydrocarbons, the other ingredient needed to form ozone. Cars sold in the United States now have catalytic converters that cut hydrocarbons by 96 percent and nitrogen oxides by 76 percent over the levels of uncontrolled cars. Other modifications allow substantial gains in fuel efficiency along with pollution reductions, despite the tendency for converters to decrease combustion efficiency. Japan's standards for automobile NO_x emissions are even stricter than those in the United States. Although European countries have made some progress in controlling automobile pollution, the large reductions possible with catalytic converters are not yet being achieved. West Germany, Austria, and Switzerland have each announced intentions to move toward lead-free gasoline, which is required in cars equipped with converters. Because so much travel takes place between European countries, other nations may be induced to follow their lead.⁷⁰

Requiring those fostering air pollution to begin controlling and paying for it will raise the price of energy and products to industries and consumers. But this in turn will encourage more efficient use of energy and materials. Few would argue that Japan's high pollution

36

control costs have seriously undermined its competitiveness in global markets. With the exception of extremely energy-intensive industries, such as aluminum smelting, most Japanese industries have accommodated the higher energy costs by using energy more efficiently. Japan's per capita energy consumption in 1982 was 2.7 times lower than in the United States and roughly 1.5 times lower than in West Germany, Sweden, Denmark, or the United Kingdom.⁷¹ Meanwhile, its air was growing cleaner, and its crops, trees, and people were all breathing easier.

Industrial countries that rely on fossil-fuel combustion for the near future must begin making it compatible with the preservation of their forests and other natural systems. This will be expensive, but by no means prohibitively so. Even with costly flue gas scrubbers, new coal plants can generate electricity more cheaply today than any other widely available energy source, except hydropower. A decade from now, coal burned cleanly will in most cases still be less expensive than nuclear power and other conventional sources. But by then several renewable energy sources may be economically competitive, and the range of energy options will have greatly expanded.⁷²

Developing countries are in a position to avoid the pollution problems for which industrial countries are now paying dearly. The renewable energy technologies now emerging alongside the large-scale centralized power grids in the industrial countries can be at the heart of energy strategies just now taking shape. Where coal power remains the best option, controlling sulfur and nitrogen oxide emissions is clearly essential and vastly cheaper if done from the start. Moreover, by taking advantage now of the breathing room conservation and increased energy efficiency provide, long-term energy plans can incorporate the new pollution technologies and broader range of energy options fast becoming technically and economically viable.

Can Forests Thrive in a Commons?

What is now unfolding in the forests of industrial countries is a tragedy of the commons on a grand scale.⁷³ Less polluted air would clearly benefit all nations, but most feel that acting to curb their own

"All but a few countries export
at least half of the sulfur dioxide they emit."

emissions, without guarantees that other nations will do likewise, will incur greater costs than it yields benefits. The dilemma derives partly from a complicated and imbalanced trade in air pollutants. All but a few countries export at least half of the sulfur dioxide they emit. Where it ends up depends largely on wind and weather patterns. At one end of the spectrum are the Scandinavian countries, with comparatively low sulfur emissions and where 75-90 percent of the sulfur deposited is imported. At the other extreme is the United Kingdom, the largest sulfur emitter in Western Europe, but which exports nearly two-thirds of its emissions and imports only 20 percent of its depositions. The numbers shown in Table 6 have wide error margins around them, but they do portray the general sulfur pollution patterns occurring on the European continent. (Data for Eastern Europe are questionable; emissions given for these countries are probably low.) In some cases countries with modest domestic emissions receive as much sulfur per unit area as the heaviest emitters. Austria, for example, has more sulfur deposited per hectare than the United Kingdom, even though it emits only one-tenth as much sulfur. Although much less is known about transfers of nitrogen oxides and ozone, these pollutants cross borders as well.

37

International cooperation is essential in controlling such a wholesale continental pollutant trade. The possibility that a nation's own control efforts may prove fruitless because of uncontrolled emissions from its neighbors is a major barrier to action. To date, attempts at achieving multilateral cooperation have been faltering at best. An important, though mostly symbolic advance was made in 1979 with the signing of the Convention on Long-Range Transboundary Air Pollution, an agreement reached within the forum of the United Nations Economic Commission for Europe (ECE). Unfortunately, the Convention required little concrete action toward reducing emissions from its signatories, although it did pave the way for cooperation in research, monitoring, and information exchange. It strengthened the Cooperative Programme for Monitoring and Evaluation of Long-Range Transmission of Air Pollutants in Europe (EMEP), which gathers data on the transport and deposition of pollutants. The Convention also was the first time that Eastern European nations entered into an environmental compact with those of the West. Emissions from these nations are especially high, and large quantities spill over into West Germany,

38

Table 6: Estimated Sulfur Emission and Deposition in Selected European Countries

Country	Annual Emissions (thousand metric tons)	Average Monthly Deposition	Density of Average Monthly Deposition (kilograms/hectare)	Share of Deposition Imported (percent)
<i>Western Europe</i>				
Austria	220	34.1	4.1	85
Belgium	410	16.1	5.3	58
France	1450	121.2	2.2	48
Greece	170	25.3	1.9	63
Ireland	130	6.5	0.9	72
Italy	1540	113.2	3.8	30
Luxembourg	20	1.1	4.2	73
Netherlands	240	17.3	4.7	77
Spain	1050	58.3	1.2	37
Switzerland	60	14.1	3.4	90
Turkey	330	41.6	0.5	58
United Kingdom	2130	84.7	3.5	20
West Germany	1750	115.8	4.7	52
<i>Eastern Europe</i>				
Bulgaria	390	34.6	3.1	56
Czechoslovakia	1690	130.1	10.2	63
East Germany	2000	77.8	7.4	36
Hungary	860	46.7	5.0	58
Poland	1250	133.0	4.3	58
Romania	1000	79.7	3.4	64
Yugoslavia	420	109.3	4.3	49
<i>Northern Europe</i>				
Denmark	230	10.9	2.5	64
Finland	290	29.3	0.9	74
Norway	70	25.5	0.8	92
Sweden	260	47.2	1.0	82

Note: The calculated deposition figures are for winter months and may vary in other seasons. Density figures are given to allow better deposition comparisons since countries vary greatly in size. Obviously loadings may vary considerably within a given country.

Sources: Emissions figures adapted from N.H. Highton and M.J. Chadwick, "The Effects of Changing Patterns of Energy Use on Sulfur Emissions and Depositions in Europe," *Ambio*, Vol. 11, No. 6, 1982. Deposition figures and calculations based on data in Environmental Resources Limited, *Acid Rain: A Review of the Phenomenon in The EEC and Europe* (London: Graham & Trotman Limited, 1983).

39

Austria, and Scandinavia. Their cooperation is thus essential to reducing pollution levels over the continent as a whole.⁷⁴

So far it appears that unless a nation is obviously victimized by acid deposition and air pollutants, it will not willingly support strong cooperative control efforts. Until recently, the United Kingdom and West Germany were strongly allied in discouraging the ECE and the European Economic Community from initiating strict controls. Yet damage to West Germany's forests brought about a dramatic and unexpected reversal of that nation's position. In June 1983, members of the ECE met in Geneva to discuss the transboundary pollution problem. For the first time, West Germany broke ranks with other European Community members by supporting a Scandinavian proposal calling for each ECE member to reduce sulfur dioxide emissions by 30 percent by 1993. Joining West Germany in supporting the proposal (put forth by Sweden, Finland, and Norway) were Switzerland, Austria, Canada, Denmark, and the Netherlands—all nations with growing concern about acid rain and pollution damage. Dissent from the United States, France, the United Kingdom, the Soviet Union, and the nations of Eastern Europe prevented the proposal from being adopted at the meeting. Instead, the Commission issued a noncommittal statement to reduce emissions where feasible. The United States stood alone in refusing to sign even this mild document.⁷⁵ Although pressured at home and from neighboring Canada to take steps to combat acid rain damage, the Reagan administration maintains that action is unwarranted until the problem is better understood.

40

The European Economic Community provides another forum for multilateral agreement. Policies receiving unanimous support from all ten member countries become binding. The EEC has in fact established Community-wide ambient sulfur dioxide standards—admittedly very lenient—with which its members must comply.⁷⁶ In early 1984, the EEC's policymaking arm, the European Commission, developed a proposal calling for substantial emission reductions from large existing power plants. The proposal requires that by 1995, total annual emissions of sulfur dioxide from these sources be reduced by 60 percent over 1980 levels; nitrogen oxides would have to be cut by 40 percent. Though a worthy effort, the proposal is unlikely to receive the unanimous agreement of all ten members, which it needs to become Community policy. The United Kingdom, Italy, France, and Greece have so far balked at setting emission limits at the Community level. Unless political pressure causes these nations to adjust their positions, a stringent EEC directive seems unlikely to emerge in the near term.

Coming to grips with the transboundary nature of long-distance pollutant transport will require a strengthening of existing institutions and very likely the creation of new ones. With the possible exception of the European Economic Community, multilateral organizations are unlikely to take action within the next several years. The best prospect for cooperation appears to be for nations to pursue bilateral and multilateral treaties among themselves. A commitment by even five of the larger European countries to require catalytic converters in automobiles would likely lead the rest of the continent to follow suit. Czechoslovakia and the West German state of Bavaria have agreed to confer on ways of protecting their diminishing forests; an important step toward bilateral East-West cooperation.⁷⁸ The United States and Canada would greatly boost the momentum for cooperative actions by agreeing, as Canada has proposed, to each cut their sulfur dioxide emissions in half.

National leaders rarely make great political gains by attacking the problems of the next generation or the country next door. The lure of short-term economic benefits too often precludes measures geared toward sustaining natural systems over the long term. Moreover, some nations are unwilling to act without irrefutable scientific "proof" of acid rain and air pollution's damaging effects—proof that may

**"Forest destruction is but an addition
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require decades of additional research. Only as pollution of the common air space claims more victims will more nations recognize the severity of the threat that lies before them and take action. Yet at some point, when the consequences become irreversible, this late-course correction strategy will fail.

41

Looking Beyond the Forest

The emerging threat to the world's forests clearly raises the potential economic and ecological consequences of acid rain and air pollution. Yet decisions to take action need not—indeed should not—rest upon what is happening in the forests alone. Forest destruction is but an addition to a litany of consequences rooted in the combustion of fossil fuels in power plants, factories, and automobiles.

Ozone levels in many agricultural regions are now high enough to damage valuable crops. In the United States, ozone is lowering the productivity of corn, wheat, soybeans, and peanuts, with losses valued at \$1.9-4.5 billion each year.⁷⁹ Vast areas of fertile farmland now regularly receive rain that is highly acidic. Although acid rain has various effects on crops, soybeans and corn have shown lower yields when grown under the acidic conditions now typical in the eastern United States.⁸⁰ Lakes and streams continue to acidify in northern Europe and eastern North America, killing fish and plant life. Acid rain and gaseous sulfur and nitrogen oxides are known to damage a host of everyday materials including paint, paper, textiles, and building stone. Corrosion of copper and lead plumbing pipes by acidic groundwater threatens to contaminate household tapwater. Aluminum and other heavy metals mobilized in acidifying soils and leached into underground drinking water also threaten human health. Like damage to forests and soils, these effects are insidious and thus hard to measure, but the potential economic loss and human suffering they may cause is staggering.⁸¹

Possibly the most serious long-term consequence of fossil-fuel combustion is the buildup of carbon dioxide in the atmosphere. Recent studies warn that within 60-80 years the carbon dioxide concentration will be twice existing levels. Because carbon dioxide allows sunlight to pass through it but traps long-wave radiation from the earth, this

42

higher concentration is expected to cause a global temperature rise on the order of 1.5°-4.5° C—an increase sufficient to raise sea levels, diminish water supplies, and alter rainfall patterns.⁸²

42 Because acid rain, ozone, and the buildup of carbon dioxide in the atmosphere are problems with a common origin, they can also have common solutions. Yet most existing and proposed strategies address isolated issues, rather than strive for the integrated solutions that are needed. Placing desulfurizing scrubbers on smokestacks, for example, will reduce sulfur dioxide and thereby control acid rain. But this technology will do nothing to help crops suffering from ozone, nothing to ensure that rain two decades from now will not be just as acidic from nitrogen oxides, and nothing to slow the rate at which carbon dioxide is increasing in the atmosphere. Technological controls for specific pollutants must be part of any plan to reduce emissions substantially in the immediate future. Yet funds are limited, and the time available for reversing these threatening trends grows ever shorter. These problems of common origin must be tackled simultaneously and at their core.

Using energy more efficiently, recycling more paper and metals, and generating more power from alternative energy sources are rarely considered in strategies to reduce air pollution or acid rain. Yet they are among the most effective and least costly ways that exist. Sulfur and nitrogen oxide emissions were lower in 1980 than they would have been without the impressive energy efficiency gains made during the seventies. Although two oil price hikes helped spur these energy savings, nations can achieve greater efficiency—and thus further reduce pollution—in the coming decades. If the United States, for example, set energy efficiency standards for just four common appliances—water heaters, refrigerators, and room and central air conditioners—between 40,000-100,000 megawatts of electricity (equal to 40-100 large power plants) would be saved *annually* by the year 2005, yearly savings that would continue into the next century. Assuming savings to be the midpoint of this range, and that half (35,000 megawatts) would come from coal-fired plants, roughly 95 million tons of coal would not have to be burned each year and 3-5 million tons of sulfur dioxide would not be spewed into the atmosphere—a 12-20 percent reduction in current annual SO₂ emissions. Installing desulfurizing scrubbers on plants producing a total of 35,000 mega-

"Because acid rain, ozone, and the buildup of carbon dioxide in the atmosphere are problems with a common origin, they can also have common solutions."

watts of power would cost \$5-10 billion; cutting sulfur dioxide by saving 35,000 megawatts through efficiency standards would cost less than one percent of this. Moreover, emissions of nitrogen oxides and carbon dioxide would be reduced at no extra cost.⁸³

43

Recycling common materials rather than discarding them attacks acid rain, ozone, and carbon dioxide buildup in two ways—directly, by reducing pollution at the production factory, and indirectly, by reducing energy demand and thus pollution emitted at the power plant. Each ton of copper produced by Canada's smelters generates an average of 2.7 tons of sulfur dioxide. Because one-third of Canada's 1980 copper supply came from recycled scrap rather than sulfur-laden ore, one million fewer tons of sulfur dioxide entered Canada's atmosphere—equal to 21 percent of the nation's 1980 sulfur dioxide emissions.⁸⁴ In virtually all nations, recycling has barely scratched the surface of its potential. Worldwide only about one-fourth of the paper and less than one-third of the aluminum used is recycled. In contrast to copper production, the feedstocks for these common materials contain little or no sulfur, but the benefits from recycling them are nonetheless dramatic: Each ton of paper made from waste paper rather than new wood reduces energy use by a third to half and air pollutants by as much as 95 percent. Aluminum produced from recycled cans rather than from virgin ore cuts emissions of nitrogen oxides by 95 percent and sulfur dioxide by 99 percent.⁸⁵

Generating more power from the wind, photovoltaic solar cells, and other renewable energy sources is central to what scientists studying the carbon dioxide problem have called a "CO₂ benign" energy strategy.⁸⁶ Added to increased energy efficiency and recycling, these alternative energy sources round out a strategy that is not only CO₂ benign, but "acid rain and ozone benign" as well. Tax policies favoring these less-polluting energy sources can compensate for the hidden environmental costs of coal burning and thereby place other energy alternatives on equal footing. Yet in the near term, the most cost-effective gains will come from further squeezing the sponges of energy efficiency and recycling. Together they will not only reduce pollution but offer a bridge to the mid-nineties when several renewable energy sources will be economically competitive. Conservation, recycling, and alternative energy sources also provide a myriad of other benefits besides cutting air pollution. Collectively they greatly

44

alter the cost-benefit calculations that are inherent in decisions about whether and how to protect forests, lakes, and crops and to prevent carbon dioxide from warming the planet.

44 The biosphere is not infinitely resilient. What is happening in the industrial world's fields and forests are signs that fossil-fuel combustion has ecological limits, and that exceeding them exacts a price. Unless energy and environmental strategies begin to reflect this, today's threats are bound to become tomorrow's catastrophes. Given the rapidity with which the forest destruction has unfolded, the relevant question is no longer whether proof of damage from air pollutants or acid rain is irrefutable, but whether the forests are sufficiently threatened to warrant action. Undoubtedly, German foresters would answer with an unequivocal yes. But the real test is whether nations so far spared severe losses will muster the political will to take action to avoid them. By encouraging energy efficiency, recycling, and the development of renewable energy sources, and by burning coal cleanly and only when necessary, nations will help protect their forests, crops, lakes, and people for generations. The connections are real, and so are the consequences of ignoring them.

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53

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54

based on *World Energy Outlook* figure that 40 percent of U. S. electricity was generated by coal in 1980 and assumption that coal's share will increase over the next two decades. Estimates of capital costs for scrubbers vary considerably. This calculation is based on a range of \$150-\$300 per kilowatt. Administering a federal program of appliance efficiency standards is estimated to cost \$3.5 million per year. (Norris McDonald, Washington representative of the Environmental Policy Institute, private communication, February 1984). Over 20 years, and assuming a 7 percent discount rate, the present value cost of the program is less than \$40 million.

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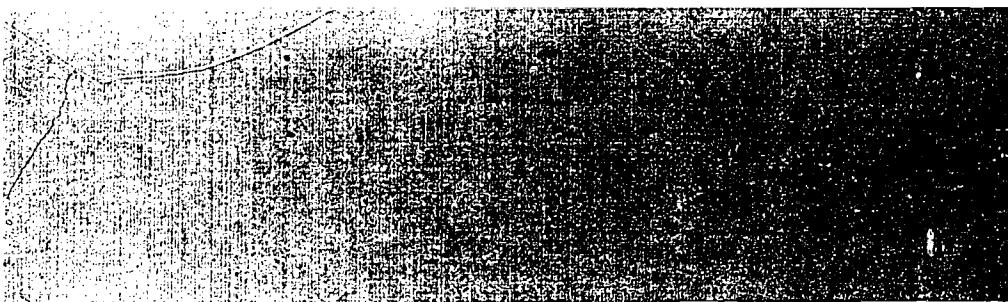
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