Acid lakes, acid rain, and nitrogen and sulfur oxides

Causes of acidification

We have discussed the causes of acid rain and acid lakes in the chapter. Briefly, sulfur and nitrogen oxides from industry, the utilities, and the transportation system interact with atmospheric water vapor to make acids, which can fall as mist, fog, rain, or snow. Wet deposition is the falling out of the acid through precipitation. Dry deposition involves gravitational unloading of the compounds on specks of acid-bearing dust or soot. Figure E14.8.1 shows the process by which the pollutants get into the environment.

The bulk of the sulfur comes from the sulfur that is in coal, which is subsequently burned in utility power plants. Most of the high-sulfur-emitting power plants are along the Ohio Valley, and the state of Ohio emits the greatest amount of sulfur of any state, followed by Texas. As discussed in the extension, the power plants targeted for emissions reduction in

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Fig. E14.8.1 How pollutants get into the environment.  
(EPA, Figure at URL http://www.epa.gov/airmarkets/acidrain)
Phase I of the CAAA are primarily located in this region. Figure E14.8.2 shows the locations of these plants.

Fig. E14.8.2 Percent differences in mean annual measured sulfate concentrations compared to projected concentrations for 1995–1996 for the eastern U.S. Small squares on the map show locations of electric utility plants affected under Phase I of the Acid Rain Program. Areas on the map depicting higher sulfate concentrations (e.g., south and east of Lake Michigan and the southwestern portion of map) appear to be due to below average precipitation volumes, which are associated with higher concentrations of sulfate. In addition, these results may have been affected by SO\(_2\) emission increases at some Phase II emissions sources that are controlled by the Acid Rain Program in the year 2000.
(Ref. 346, Fig. 7-2)

Table E14.8.1 lists the sources of air pollutants for 1998. While most of the sources of the various pollutants listed in the table have been discussed so far in this book, ammonia is a pollutant that gets into the environment because of agriculture.\(^{(218,367-369)}\)
TABLE E14.8.1

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emissions (million tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anthropogenic Emissions:</strong></td>
<td></td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>81.15</td>
</tr>
<tr>
<td>Lead</td>
<td>$3.60 \times 10^{-3}$</td>
</tr>
<tr>
<td>Nitrogen Oxides</td>
<td>22.18</td>
</tr>
<tr>
<td>Particulate Matter (PM$_{10}$)</td>
<td>31.52</td>
</tr>
<tr>
<td>Miscellaneous and Fugitive dust</td>
<td>28.03</td>
</tr>
<tr>
<td>Nonfugitive dust</td>
<td>3.48</td>
</tr>
<tr>
<td>Sulfur Dioxide</td>
<td>17.83</td>
</tr>
<tr>
<td>Volatile Organic Compounds</td>
<td>16.26</td>
</tr>
<tr>
<td><strong>Biogenic Emissions:</strong></td>
<td></td>
</tr>
<tr>
<td>Volatile Organic Compounds a</td>
<td>25.57</td>
</tr>
<tr>
<td>Nitric Oxide a</td>
<td>1.39</td>
</tr>
<tr>
<td>Particulate Matter (PM$_{2.5}$)</td>
<td>7.60</td>
</tr>
<tr>
<td>Miscellaneous and Fugitive dust</td>
<td>4.95</td>
</tr>
<tr>
<td>Nonfugitive dust</td>
<td>2.65</td>
</tr>
<tr>
<td>Ammonia</td>
<td>4.48</td>
</tr>
<tr>
<td>Hazardous Air Pollutants</td>
<td>5.37</td>
</tr>
</tbody>
</table>

\(^a\) 1997 value, 1998 not available
Source: Ref. 218, Table ES-2

The midwest has the highest sulfate concentrations, greater than 7 µg/m$^3$ (adjacent to the Ohio Valley and in northern Alabama, the locations of large electric utilities shown in Fig. E14.8.2), and the area of the highest concentration has not changed as overall emissions have declined. Electric utilities account for over two-thirds of the SO$_2$ emissions in the eastern United States.$^{(346)}$ Fig. E14.8.3 shows how sulfur and sulfate have changed in the 1990s in the U.S. and Germany, as we have already pointed out. Clearly, this has decreased the sulfur contribution to acid deposition.

Much nitrogen is added on purpose as fertilizer, so humans are changing soils both by inadvertence and on purpose. The change of forest to farmland has meant a decline in the amount of carbon that can be stored in vegetation.$^{(368)}$
b. SO$_2$ concentrations in Germany decreased between 1985 and 1995.

(a and c, Ref. 346, CASTNet data, Fig. 7-5 a and b; b, Ref. 360, Fig. III.3)
Fig. E14.8.4 a. Ambient total nitrate concentrations in the rural eastern U.S., 1990–91 vs. 1997–98. b. Ambient ammonium concentrations in the rural eastern U.S., 1990–91 vs. 1997–98. (Ref. 346, Fig. 7-5)

Fig. E14.8.4 shows how nitrate and ammonium concentrations have not changed substantially during the same time interval as used to examine sulfur. Further, the highest nitrate concentrations are found in the states of Ohio, Indiana, and Illinois, some of the
same states that are the prime sulfur emitters. That the midwest is a major generator of pollution—including agricultural pollution—that becomes acid rain is obvious from the diagrams.\(^{(218,346,367,370)}\) While half the nitrogen in ammonia comes out of the atmosphere with 50 km, much is transported far away. Most acidity problems in the region from eastern New York through New England stem from long range transport from the Ohio Valley.

**Where acidification has affected the environment**

As expected, regions having a pH more acid than 4.2 are centered around the area of highest SO\(_2\) emission seen in Fig. E14.8.3, as is apparent in Fig. 13.8.5.\(^{(371)}\)
Acid rain on fields and forests

The result of all this acid deposition is to affect watersheds and surface water. Figures E14.8.7 and E14.8.8 shows the regions of the United States having acidic surface water. Clearly, these figures show that where there is scant ability for the environment to neutralize acid, acid will appear. While these regions are not the prime agricultural regions of the country, they play a significant role. And, as noted above, the midwest keeps a large share of its nitrate and ammonia load. So regions subject to acid rain effects will include farmland and forest. The acidity of precipitation is not decreasing as much as would be expected given the drop in emissions.\(^{(372)}\)
What effects could acid rain have on farmland and crops? Cape studied this problem and identified some consequences to which most researchers agree.\(^{(373)}\)
• leaf injury and growth reduction occurs when the pH is below 3;
• increased shoot utilization of photosynthetic energy relative to the roots;
• new leaves are most susceptible, and injury occurs first to surface cells;
• leaf surface characteristics (wettability, buffering capacity, transport of material across the leaf’s surface) contribute to susceptibility and differ among species;
• greenhouse data does not predict effects on plants grown in the field very well;
• there are large intraspecies differences in response;
• timing of exposure to pollution is of greatest importance; and
• plants may be able to recover from or adapt to injurious exposures.

Cape also claimed that the damage from exposure to a series of gas or liquid pollutants would not be more injurious than exposure to individual pollutants, but other research shows that interactions do occur.\(^{(374)}\)

In forests, acid rain can have both direct effects on vegetation, and indirect effects—effects on soils, that then affect plants.\(^{(375)}\) There are several experimental forests in the northeast, most prominently Harvard Experimental Forest (Massachusetts) and Hubbard Brook Experimental Forest (New Hampshire), which has allowed the effects of emissions on forest environments to be gauged.

Forest regrowth has a higher capacity than undisturbed forests to accumulate the nitrogen that acid rain brings.\(^{(367)}\) Longterm nitrogen accumulation is major factor in reducing negative impacts of nitrogen deposition on forests and surface waters.\(^{(367)}\) Fungi are the major nitrogen assimilation agent in the soil.\(^{(367)}\) More than two-thirds of the added nitrogen is found in soil organic matter.\(^{(367)}\)

The Hubbard Brook Experimental Forest, established in the 1960s, provides a decades-long record of very detailed measurements on the effects of acid rain on the forest’s
ecology. At Hubbard Brook, the observed rate of accumulation of forest biomass basically dropped to zero in 1987 and has stayed extremely low ever since. (376,377)

Acid mist has been found to have “profound” physiological effects. (372) For example, red spruce and sugar maple have been studied extensively, and have been shown to be affected directly by acid deposition. Presumably, while the effects on other species of tree may not be as strong, they are present. Acid fog or mist attacks the protective wax coating on conifer needles; it may be thinned or eliminated and essential nutrients in tree leaves and needles can be stripped away. (370) Direct deposition on red spruce needles is a stress that apparently removes calcium, causing the tree to suffer from calcium deficiency that may not be obvious. (372,375) Red spruce winter injury is caused by subfreezing temperatures—acidic cloud water reduces cold tolerance and low calcium levels robs cold tolerance in red spruce. (372) This makes these trees susceptible to freezing injury. (372) Many canopy trees in some areas of the Northeast (more than half of old growth red spruce in the Adirondack Mountains of New York and the Green Mountains of Vermont and approximately one-quarter of old growth red spruce in the White Mountains) have died as a result. (370) Sugar maple dieback has occurred at high elevations with poor soil in Pennsylvania, apparently caused by stress due to the depletion of nutrient cations (Ca$^{2+}$ and Mg$^{2+}$). (370) While tree deaths in parts of the Adirondacks and New England in recent years were attributed mainly to shifts in the regional climate, Driscoll et al. suggest that the trees were weakened first by acidified soils, which made them less able to withstand climate changes. (370)

Cations are positive ions that arise when mineral bases dissolve in water. (376) As a result, they are sometimes called “base cations.” Production of the cations by the action of the weather—wind, rain, and so on, on exposed rock and sand (“mineral weathering”)—is the primary source for base cations in most forests, although atmospheric deposition may
provide important inputs to sites with very low rates of supply from mineral sources.\(^{(370)}\) These cations have also been observed to come from the atmosphere, and Hedin and Likens argue that this results from neutralization of acidity in atmosphere on dust particles, so dust particles undo part of the effects of acid rain.\(^{(376)}\) The resultant cations are deposited everywhere as they fall out of the atmosphere and can even help neutralize the effects of unneutralized acid rain when it reaches the ground. The numbers of such atmospheric cations has declined steeply in the 1990s.\(^{(376,377)}\) This means that the success of the CAA and CAAA in reducing particulates has increased the ability of the reduced concentration of sulfates to cause acid rain.

**Acid rain on soils**

Soils naturally contain base cations, and they are part of a natural buffering system. Atmospheric base cations constitute a major additional supply. Over many years, acidic deposition contributed to the depletion of the natural base plant nutrient cations (K\(^+\), Ca\(^{2+}\), and Mg\(^{2+}\)) from soils in many areas.\(^{(370,376)}\) In most forests a hundred years ago, base cations were stored in the soil; in a few forests, the atmospheric cations were the major base cation source.\(^{(376)}\) However, atmospheric cations were important even in forests with stored cations. If the supply of base cations is sufficient, the acidity of soil water can be neutralized.\(^{(370)}\)

In recent times, atmospheric bases have declined substantially—at Hubbard Brook, there has been a 49% decrease since 1965; while at Sjöängen forest in Sweden, a 74% decrease has been measured since 1971.\(^{(376)}\) In any soils, cations are depleted if they are exposed to acid precipitation.\(^{(376,377)}\) According to a review article by Driscoll et al.\(^{(370)}\) that studied many issues pertaining to acid rain, “acidic deposition has enhanced the depletion of exchangeable nutrient cations in acid-sensitive areas of the Northeast.”\(^{(370)}\) Soil in the
northeast is generally poorer, and it is more deficient in base cations now than 50 years ago because precipitation contains many fewer cations now.\textsuperscript{(376,377)}

Soils that used to be able to neutralize acid have lost their acid neutralizing capacity as nitrogen and sulfur compounds have been chemically incorporated in the soils. The Hubbard Brook forest soil has become depleted in potassium, calcium, and magnesium ions.\textsuperscript{(370,376)} It is believed that the decline in base cations is the key to decline of eastern forests.\textsuperscript{(370,376)} The cation-deficient soils become acidified soils that are no longer able to protect downstream systems from the acid in acid rain.\textsuperscript{(376)}

It has been found that calcium in Hubbard Brook soil has shrunk by up to 50\% in last half century.\textsuperscript{(370,377)} Experiments have shown that a greater amount of calcium leaching occurs at an acid pH of 3 than at the more neutral pH of 5.\textsuperscript{(367)} Nitrogen additions can lead to nitrate and aluminum mobility in soils.\textsuperscript{(367)} Aluminum mobilized in mineral soil by acid deposition reduces soil storage of calcium and availability to roots.\textsuperscript{(372)}

Because the soils have incorporated the excess nitrogen and sulfur compounds over many years of acid deposition, even as the emissions levels have decreased the acid levels have remained high, both because the soils can no longer process the acid chemically, and because there is such a large stored reservoir that it will take a long time before the soils will be restored. This will impose a delay in recovery in the streams and lakes that drain the watershed.\textsuperscript{(370)} After so many years, decades, of acid exposure, it should be no surprise that it will take decades to restore.

Driscoll et al.’s review article (Ref. 370) estimated that during the history of the forest that became the Hubbard Brook Experimental Forest, wet plus dry deposition increased from 7 kg/ha/yr in 1850 to 68 kg/ha/yr in 1973, with subsequent decline.\textsuperscript{(370)} A
comparison with Fig. E14.8.5, where the average deposition over the eastern half of the country is 25 kg/ha/yr, shows both how immense the human-caused problems are, and can see improvement. During that 150 years, sulfur deposition increased by factor of 5.\(^{(370)}\)

There are general concerns that acidic rain will adversely affect wildlife. For example, there appears to be strong evidence that the wood thrush’s breeding success has plunged as a result of acid rain.\(^{(378)}\)

**Acidified streams and lakes**

Some lakes are naturally acidic; they contain organic anions (negatively charged ions) instead of the anthropogenic inorganic sulfate (SO\(_4^{2-}\)), nitrate (NO\(_3^-\)), chloride (Cl\(^-\)), and bicarbonate (HCO\(_3^-\)) ions. Sediments show that only seven Adirondack lakes were acidified before industrialization.\(^{(379)}\) The average acidity of Adirondack lakes (from all sources) has increased over the past 50 years by a factor of 40.\(^{(307)}\) At Big Moose Lake, acidification took place over 30 years, with a start long after the peak sulfur emission, in 1920.\(^{(380)}\) Only 4% of these lakes were acid during the period 1920-1937, but by the 1970s, over half were acid.\(^{(381,382)}\)

Some 50,000 lakes in Canada may be destroyed by acid rain \(^{(383)}\) (see Fig. E14.8.7), and many other lakes in the northeastern United States have shown increases in acidity.\(^{(357)}\) One of the most acidic lakes on record is Little Echo Pond in Franklin, New York, which has a pH of 4.2.\(^{(384)}\) Nine percent of lakes in the northeast have pH less than 5.5, while 20% of the lakes in Florida have pH values so low.\(^{(364)}\) The review of Driscoll et al. found data that show that 41% of lakes in Adirondacks were “chronically acidic,” most controlled by Ca and Mg ions. Of the acid lakes, 83% were dominated by inorganic ions;
therefore, 17% represent naturally acidic lakes dominated by recurring organic anions.\(^{(370)}\) During the 1990s, while emissions were relatively constant, the level of nitrogen rose in 48 percent of the 52 Adirondack lakes that are routinely tested for acid levels by the nonprofit Adirondack Lakes Survey Corporation.\(^{(385)}\)

The rate of deposition in Europe has also been large enough to acidify many lakes there. Even though the largest deposition is in Poland and the eastern part of Germany, the first lakes to acidify were in Scandinavia. In Scandinavia, the soils were poor in buffering capacity, while in Europe, the acid leached the cations out over a long time.\(^{(380)}\) The sudden advent of *Waldsterben* and *Waldschäden* (Chapter 12) in the 1980s was part of a progression. There has lately been a reduction of acid rain of 50% to 60% in western Europe due to tighter regulations.\(^{(386)}\) However, it is not yet clear whether this will do enough. Fifty-seven percent of Europe is receiving sulfur above the critical load.\(^{(380)}\) The scope of the acid lake problem is beyond huge. According to Environment Canada, for example, the Sudbury, Ontario nickel mines and smelters released so much sulfur dioxide that an estimated 7000 lakes in a zone of about 17,000 square kilometers were acidified.\(^{(387)}\) Pollution control equipment installed in the 1990s reduced local emissions by about 90%.

If acid snow falls on a region during winter, the spring snowmelt can bring great increases in the amount of acid water flowing into lakes, with corresponding decreases in pH. The results of a study of a lake in Ontario are shown in Fig. E14.8.9.\(^{(381)}\) Even if the lake itself is not acidic, the *acid shock* can cause problems for lake fauna, especially fish.\(^{(388)}\)
Fig. E14.8.9 Spring pH depression in one stream flowing into Harp Lake, Muskoka, Canada. The spring runoff produces a severe acid shock to stream biota. (Courtesy Ontario Ministry of the Environment)

Although the health effects of airborne sulfur and nitric oxides are not totally certain, the effect of the acids on bodies of water and the bodies of its inhabitants is much better known. Acidified water attacks the surface of the skin, increasing the permeability.\(^{389}\)

As the concentration of acid increases, fish experience reproductive difficulties (Fig. E14.8.10). Any lake with a pH below 7.0 is somewhat acidic. Below a pH of 5.5, most species are endangered, and the lake is classified as acid. Fish growth is retarded, the salt balance in the blood is set awry, calcium is depleted from the skeleton (leading to malformation), mercury may be absorbed,\(^{36}\) and aluminum clogs fish gills.\(^{390-392}\)
An experiment has been conducted since 1976 in which lakes in northern Ontario have been artificially acidified to see possible effects.\(^{(393)}\) Fish became more obviously misshapen as the acidity increased. It appears that in this lake, irreversible changes in the ecosystem occurred at a pH of 5.8 (earlier in acidification than had been believed before); no fish reproduced at pH values below 5.4.\(^{(394,395)}\) Below a pH of 4.5, most life is gone except for algae, moss, and fungi. The lake can remain clear, or it may be matted with algae blooms and mosses. Originally, it was thought that a pH of 5.5 was the limit, since many sport fish could tolerate these levels. That is too low. Many organisms lower on the food chain are harmed at much higher pH. Also, aluminum is released (and is toxic). Lakes themselves, as well as the surrounding watersheds, resist acidification.\(^{(393)}\)

Aluminum is often found in water at small concentration. Its concentration increases as pH decreases as it becomes mobilized in the soil and is leached out.\(^{(382)}\) Both low pH and increased aluminum levels are directly toxic to fish, a double whammy. Why should it be
implicated so strongly in toxicity to fish in acid lakes? We know that aluminum is toxic in humans. It is directly associated with syndromes that mimic senility, which occur in patients with chronic kidney failure, dialysis encephalopathy, and osteomalacia,\(^{(396)}\) and it is implicated in certain brain disorders, such as senile dementia, Alzheimer’s disease, and Parkinson’s disease.\(^{(392)}\) Patients with such brain malfunction have high aluminum content in their brain tissue (called neurofibrillary tangles). No aluminum deficiency has ever been identified in living organisms.\(^{(396)}\) Aluminum appears to be harmless to most animals as long as calcium levels are maintained. When calcium is in short supply, aluminum may replace it, causing the problems already mentioned.\(^{(392)}\)

Aluminum leached out from stream and lakeshore soils seems in some cases to be more the problem for animals living in the lakes and streams than the acid itself.\(^{(392)}\) The concentration of aluminum that is lethal to half the animals, \(LD_{50}\), is presented in Table E14.8.2\(^{(396)}\) for several aluminum-containing compounds.
TABLE E14.8.2

Concentration of Aluminum Compounds Fatal to Half the Experimental Animals

<table>
<thead>
<tr>
<th>Compound</th>
<th>pH</th>
<th>animal</th>
<th>LD$_{50}$ (µmol/mol(^\dagger))</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlCl$_2$6H$_2$O</td>
<td>7-8</td>
<td>Goldfish</td>
<td>1.0</td>
</tr>
<tr>
<td>AlCl$_3$</td>
<td>7.4±1</td>
<td>Trout</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Goldfish</td>
<td>0.15</td>
</tr>
<tr>
<td>AlCl$_3$ aqueous</td>
<td>4.9-5.2</td>
<td>Trout fry</td>
<td>0.5-1.0</td>
</tr>
</tbody>
</table>

\(\dagger\) Also known as part per million, ppm

In another acidification experiment in Norway, two lakes were acidified, one with sulfuric acid and the other with both sulfuric and nitric acid.\(^{397}\) Soil acidification will inevitably result at the lakes being acidified; about 80\% of added acid is in the soil. There was increased runoff of calcium and magnesium in the acidified lakes.\(^{397}\) An acidified lake was fed pure water (and protected from outside water by a roof) as a control.

Liming (adding calcium to) lakes to ameliorate damage from acid rain does not restore the lake, and of course it is only a stopgap measure—and it can be expensive (see Table E14.8.3).\(^{391}\)

TABLE E14.8.3

Cumulative Cost (Millions of 1990 Dollars) of pH Stabilization from 1990 to 2010

<table>
<thead>
<tr>
<th>Number of Lakes</th>
<th>Cost of Liming</th>
<th>Cost of Monitoring</th>
<th>Cost of Stocking</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program Remains Constant</td>
<td>32</td>
<td>$0.11</td>
<td>$0.07</td>
<td>$0.23</td>
</tr>
<tr>
<td>Program Grows by Two Lakes per Year</td>
<td>72</td>
<td>$0.16</td>
<td>$0.10</td>
<td>$0.35</td>
</tr>
</tbody>
</table>

Source: Ref. 347, Table E-18
Since deposition is decreasing, there is hope that the acid rain/acid soil/acid stream/acid lake problem will eventually become less of a problem. However, over a thousand streams in the east are acidified because of acid deposition, with the Pine Barrens region of New Jersey almost totally acidified.\(^{(384)}\) Hubbard Brook still has acidic streamwater even after the decreases in emissions in the 1980s and 1990s, for the reasons mentioned in the preceding section. “Sulfur or nitrate pools” of acid soils have built up in forests and continue to release their acidity.\(^{(370)}\) According to the Virginia Trout Stream Sensitivity Study results,\(^{(398)}\) acidification has continued in most brook trout streams. The survey monitored 58 streams quarterly over 12 years, and found that acid levels have increased in 43 streams while decreasing in 15.\(^{(398)}\) At the same time, the number of highly acidic streams (with lethal effects on brook trout) increased. This suggests that, for Virginia, the mixed stream degradation results could be an indication that decreasing deposition will ultimately mean a smaller problem magnitude.\(^{(398)}\)

Overall, the ability of surface waters in New England to buffer acidity has increased slightly, and the Adirondack and Catskill regions have experienced no significant improvement since atmospheric sulfur deposition has decreased.\(^{(353,370,399)}\) Additionally, as the Driscoll et al. review article (Ref. 370) indicates, “acidification of surface waters has resulted in a decrease in the survival, size, and density of fish and in the loss of fish and other aquatic biota from lakes and streams.”

Lakes can recover by themselves when acidification ceases, but the natural process is very slow—perhaps 50,\(^{(370)}\) perhaps hundreds of years.\(^{(393)}\) Approximately 500 Swedish lakes are being limed,\(^{(400)}\) and so are other European lakes.\(^{(386)}\) Americans are borrowing the costly Swedish technique (Table E14.8.2); about 100 American lakes are being limed.\(^{(400,401)}\)
Acid rain has been responsible for environmental degradation. Our agricultural production, and therefore our lives, depends on the proper functioning of the ecosystems all over the world. In the spirit of the Tragedy of the Commons, we often ignore or abuse our ecosystems, but we need them. Daily has listed the value of ecosystems, reproduced here as Table E14.8.4.

**TABLE E14.8.4**

Ecosystem Services

- Purification of air and water
- Mitigation of floods and droughts
- Detoxification and decomposition of wastes
- Generation and renewal of soil and soil fertility
- Pollination of crops and natural vegetation
- Control of the vast majority of potential agricultural pests
- Dispersal of seeds and translocation of nutrients
- Maintenance of biodiversity, from which humanity has derived key elements of its agricultural, medicinal, and industrial enterprises
- Protection from the sun’s harmful rays
- Partial stabilization of climate
- Moderation of temperature extremes and the force of winds and waves
- Support of diverse human cultures
- Providing of aesthetic beauty and intellectual stimulation that lift the human spirit


While the pollution trading system in place has worked to reduce overall emissions, in some regions, emissions have increased (in a zero-sum game, there must be winners and losers). Everything being equal, the reductions experienced are supposed to make everyone winners in the long run. Ohio is ranked “first” as emitter of both sulfur oxides and nitrogen oxides (Texas is sixth in sulfur emissions and second in nitrogen oxides).\(^{(402)}\)
Which states are the greatest buyers of air pollution allowances? Ohio, with 40,926,313 allowance permits purchased is first, and Texas, with 26,421,520 allowance permits is second.\(^{(233)}\) New York, which is downwind of Ohio, has realized that if a New York utility sells an allowance to Ohio, the pollution will wind up traveling through New York. It has therefore forbade the New York utilities to sell allowances to Ohio and other upwind states.\(^{(403)}\)

Finally, Driscoll et al. (Ref. 370) point out that “emissions of air pollutants have important linkages to other large-scale environmental problems, including coastal eutrophication, mercury contamination, visibility impairment, climate change, and tropospheric ozone.” Can we avoid costly environmental mistakes? Can we find ways to minimize these problems or to recover from them? Will continuation of reductions in pollutants allow the streams and lakes of the industrialized world to recover while not endangering those in as yet unspoiled regions? We are still too ignorant to know what we have to know to be able to find answers to these questions. As Hedin and Likens add, “[s]imple solutions do not always work in complex ecosystems.”

**Progress in controlling acid rain**

The CAAA did have an effect in reducing sulfur and nitrogen oxides in the air, thus reducing the acidity of rain. Figures E14.8.11 and E14.8.12 show the difference in wet deposition of sulfur and nitrogen (essentially sulfuric and nitric acid rain), respectively, between two three-year periods a decade apart. The midwestern states, especially Ohio, West Virginia, Indiana, and Pennsylvania are still trouble spots for both sorts of acid rain, but less so than a decade previously.
The last word in pollution: Visibility reduction redux and holoacetic acid

Because the sulfur dioxide and nitrogen oxides tend to gather on dust particles or cause particles to grow around them, they tend to scatter light equally—to become a source of haze. The haze in the eastern part of the country is mainly sulfate in origin, with the
remainder caused by nitrates and VOCs. In California, haze is mostly caused by nitrate aerosols, with VOCs also participating.

Environment Canada has raised concerns about compounds known as holoacetic acids, recently identified in Canadian waters and subsequently found elsewhere in industrialized settings. These compounds, such as trichloroacetic acid, thought to form from industrial chemicals tetrachloroethene and 1,1,1-trichloroethane, act as poisons to plants and are suspected to be carcinogens.(404)