Acid Rain

What is Acid Rain?

The term acid rain, as commonly used, refers to rain, snow, or fog containing a dilute solution of sulfuric acid and nitric acid, formed mainly from pollution associated with fossil fuel combustion. Other terms for this phenomenon are acid precipitation and wet deposition. Wet deposition accounts for about half of all acidic deposition.

Acid deposition also occurs through dry deposition of acidic gases and particles. This material is deposited onto trees, buildings, cars, and homes. Dry-deposited gases and particles can be washed from surfaces by rainstorms. The acidic runoff combines with wet-deposited acid precipitation and further impacts the environment.

Eastern North America and northern Europe are most known for their acid deposition problems. These forested areas of the globe have humid atmospheres, providing the water content needed to convert sulfur oxides and nitrous oxides to acids. In more arid regions such as the American West, airborne dust originating from alkaline soils provide a natural means of neutralizing sulfur oxides and nitrogen oxides. Acid deposition tends to be minimal in relatively dry areas.

The term acid rain was coined in 1852 by English chemist Robert Angus Smith, who noted a connection between London's air pollution, caused by industrial activity, and its acidic rainfall. Large-scale effects of acid deposition were not recognized until the mid-20th century. Environmental regulations to control industrial emissions of sulfur dioxide, a major source of acid deposition, began in 1990 in the United States.

How is Acid Rain Formed?

The primary cause of 'acid rain,' more accurately called acid deposition, is air pollution from burning fossil fuels. Fossil fuel use does not directly emit acids into the atmosphere. Instead, it releases large amounts of acid precursors, primarily sulfur oxides (SOx) and nitrogen oxides (NOx). When exposed to the atmosphere, these react with water to form sulfuric acid and nitric acid, components of acid deposition.

Sulfur dioxide (SO2) is emitted through combustion of fossil fuels containing sulfur as an impurity. Coal combustion is by far the major source of sulfur dioxide emitted into the atmosphere. During combustion, sulfur is oxidized to form sulfur dioxide (SO2). Sulfur dioxide rises into the atmosphere and is oxidized once again in the presence of atmospheric hydroxyl radicals to form sulfur trioxide (SO3). Sulfur trioxide reacts with atmospheric water droplets to form sulfuric acid (H2SO4). Sulfur dioxide emission is the most common contributor to acid deposition, responsible for about 70% of the total. The greatest source of sulfur dioxide is electrical utility plants, which pump approximately 15 million tons of SO2 into the atmosphere each year, out of the total 22 million tons generated annually by human activities. Other contributors of sulfur dioxide include industrial processes and automobiles and other motor vehicles.

Nitrogen oxides (NOx) are also formed through fossil fuel use. In contrast to sulfur, nitrogen is not an impurity but rather an integral part of the organic material making up fossil fuels. Fossil fuel combustion releases nitrogen into the atmosphere, usually in the form of nitric oxide (NO). Nitric oxide (NO) is oxidized by atmospheric molecules, such as ozone (O3) or hydrogen dioxide (HO2), to form nitrogen dioxide (NO2). Nitrogen dioxide (NO2) reacts with OH in the atmosphere to form nitric acid (HNO3). Nitric acid can also form when nitrogen dioxide (NO2) reacts with the nitrate radical (NO3) in the presence of atmospheric water or aldehydes. Nitrogen oxides account for approximately 30% of all acid deposition. Major sources of nitrogen oxide emissions are automobiles and fossil fuel burning power stations.

Nitric acid and sulfuric acid eventually fall back to the Earth's surface as acid deposition. This precipitation can be wet (rain, snow, or fog) or dry (gases or acidic salts).
The pH Scale

The pH scale measures how acidic or basic a substance is. It ranges from 0 to 14. A pH of 7 is neutral. Values less than 7 are acidic, while those greater than 7 are basic. Each whole pH value below 7 is ten times more acidic than the next higher value. For example, a pH of 4 is ten times more acidic than a pH of 5, and 100 times more acidic than a pH of 6.

Pure water is neutral, with a pH of 7.0. When chemicals are mixed with water, the mixture can become either acidic or basic. Alkaline is another word for basic.

Vinegar and lemon juice are acidic, while laundry detergents and ammonia are basic. Mixing acids and bases can cancel out their extreme effects, similar to the way mixing hot and cold water can even out the temperature.

Normal rain is slightly acidic, with a pH of approximately 5.6. Precipitation with pH less than 5.6 is considered acidic. In the year 2000, the most acidic rain falling in the United States had a pH of about 4.3.

Environmental Effects of Acid Rain

Acid rain, more accurately termed acid deposition, has been studied for many years. Numerous environmental effects have been attributed to acid deposition. Perhaps one of the best-known is acidification, a condition in which lakes and streams have a low pH level, resulting in the death of fish and other animal and plant life. Acidification can be chronic, where a given surface water body has a constantly low pH value, or episodic, where pH levels decrease for brief periods due to runoff from melting snow or heavy rain.

U.S. areas prone to chronic acidification include the Adirondacks and Catskill Mountains in New York State, the Appalachians, the upper Midwest, and mountainous areas in the western U.S. One of the most acidic lakes in the U.S. is Little Echo Pond in Franklin, New York, with a pH of 4.2. In the New Jersey Pine Barrens, over 90% of streams are acidic.

Episodic acidification, which can be severe enough to cause fish kills, is common in the mid-Appalachian region, where it affects approximately 30% of sensitive streams, and in the Adirondacks, where 70% of sensitive lakes are at risk.

In eastern Canada, 14,000 lakes are extremely vulnerable to chronic acidification. Acidification also occurs in much of Scandinavia and in parts of the United Kingdom and the Alps.

Forest damage is another environmental effect related to acid deposition. A 1999 survey of European forests showed that one out of every four trees had suffered the loss of 25% or more leaves or needles. Tree damage is believed to have multiple causes, including acidification of soil and high concentrations of ground-level ozone, both side-effects of acidic deposition. In Germany, this phenomenon, first observed in the Black Forest in the 1960s, is termed Waldsterben or tree death. An example is shown in the photo above. Damage was first observed in conifers, then later in deciduous trees, such as oak and beech. By 1990, nearly half the trees in the Black Forest were damaged.

Soils are also affected by acid deposition, particularly in areas with highly siliceous bedrock (granite, gneisses, quartzite, and quartz sandstone). These soils, which are common in eastern North America and Scandinavia, are already somewhat acidic. When acid deposition occurs on acidic soils, important cations including potassium, calcium, magnesium, and sodium are readily leached out, making them unavailable to plants as nutrients. This phenomenon, termed soil depletion, reduces the fertility of the soil. Similarly, in areas with old, highly leached soils, acid deposition depletes the small amounts of cations present, and the soil soon becomes unable to support plant life.

In contrast, soils rich in calcium, potassium, magnesium, and sodium are more resistant to the effects of acid deposition. These soils, common in arid and semi-arid regions such as the Utah desert shown above, are naturally alkaline and have the ability to buffer acid deposition. Much of the western U.S. is at less risk for acid deposition for this reason. The buffering capacity of alkaline soils can, however, be depleted by continuous acid deposition.

Many plants and animals are sensitive to
acidification. The vulnerability of fish and other small aquatic organisms is well-established. As acid precipitation flows through soils, aluminum is released. As pH in a lake or stream decreases, aluminum concentration increases. Both low pH and high aluminum concentrations are toxic to fish. Frogs are relatively tolerant of low pH, but the insects upon which they feed are not. Lichens, mosses, and fungi are also particularly sensitive to acid deposition.

Human health is indirectly affected by acid deposition through the consumption of toxic metals that entered the food chain during soil acidification.

Other environmental problems are closely related to acid deposition. Eutrophication is a term used to describe aging of a lake or shallow marine areas such as coastal zones. The aging process can be natural, resulting from the accumulation of nutrients, sediments, silt, and organic matter in from the surrounding watershed. Eutrophication can also be caused by human activity. This is called cultural eutrophication and is associated with excess nitrogen and, to a lesser extent, excess phosphorous, from agricultural activities, sewage, and industrial waste. Algal blooms, such as the red tide event in coastal Hong Kong illustrated above, are a symptom of eutrophication. If eutrophication is ongoing, a decline in biodiversity may result.

Ground-level ozone is formed in the atmosphere by nitrogen oxides and volatile organic compounds in the presence of sunlight. Ground-level ozone causes damage to agricultural crops and trees, and is harmful to human health. Ground-level ozone commonly reaches harmful concentrations in cities around the world. It is particularly problematic in urban areas with heavy motor vehicle traffic combined with a tendency to trap local air pollution, such as through temperature inversions or by nearby mountain ranges.

Acid deposition is well-known for its corrosive effects on buildings and monuments made of sensitive materials such as limestone or sandstone. An example is shown at left. These easily weathered materials are slightly soluble in normal rainwater. In the presence of acid deposition, weathering rates are greatly increased.
control is achieved using an innovative strategy called cap and trade. Under the cap and trade approach, permission to emit sulfur dioxide is assigned to individual electrical utilities in the form of allowances. An allowance is an authorization to emit one ton of sulfur dioxide in a year. At the end of a given year, each electrical utility must hold an allowance for each ton of sulfur dioxide it emitted. Unused allowances may be carried over into future years, or sold to other companies. Companies seeking to build new power plants must purchase allowances from the existing pool. New allowances are not added as the purpose of the program is to limit the total quantity of sulfur dioxide emitted nationwide regardless of increased demands for electrical power. The sulfur dioxide cap and trade program has met its goals since its start in 1995, and is expected to continue to be successful.

Nitrogen oxide emissions are treated differently under the U.S. Acid Rain Program. A goal of the program is to reduce nationwide nitrogen oxide emissions by 2 million tons by 2010. To reach this goal, a maximum emission rate is established for each power plant, depending on the types of boilers installed at each plant. An overall ceiling value has not been set for nitrogen oxide emissions. Nationwide in the U.S., nitrogen oxide emissions have remained constant at about 23 million tons per year since the 1980s. Although nitrogen oxide emission rates have declined with the use of cleaner technologies, total electricity generation and vehicle use have increased.

In 1991, the United States and Canada formalized their cooperation on acid precipitation concerns by adopting the Canada-United States Air Quality Agreement. Under this agreement, Canada committed to a permanent national cap for sulfur dioxide emissions of 3.2 million tons per year by the year 2000. The United States committed to a permanent national cap for sulfur dioxide emissions of 8.95 million tons per year by 2010, the same level as mandated under the Clean Air Act Amendments of 1990. For nitrogen oxides, Canada committed to reduce stationary source (power plants and other industry) emissions by 100,000 tons by the year 2000, and the U.S. committed to reduce total nitrogen oxide emissions by 2 million tons by 2000. Both countries agreed to improve nitrogen oxide controls for motor vehicle sources. To date, all the goals of the Canada-United States Air Quality Agreement have been met.

What is being done in Europe?

In 1979, 34 countries in North America and northern Europe established the Convention on Long-Range Transboundary Air Pollution. The Convention was an agreement to adopt economically feasible solutions for limiting sulfur dioxide and nitrogen oxide emissions. Although this agreement did not have specific guidelines, it did establish global awareness of acid precipitation. In 1983, 21 European countries made a commitment to reduce sulfur dioxide emissions by 30% within 10 years. In 1988, 12 countries had already reached this goal. Also in 1988, a piece of legislation called the EC Large Combustion Plants Directive was implemented throughout Europe. This legislation required all European industry to reduce nitrogen oxide emissions by 40% by 1998 and sulfur dioxide emissions by 58% by the year 2003.

By the late 1990s, studies revealed that acid precipitation legislation had been successful in reducing sulfur dioxide emissions in western Europe. In 1996, the Norwegian Institute of Air Research revealed there was a significant decline in sulfur dioxide emissions in southern Norway. After measuring sulfur concentrations in the air, rainfall, lakes and streams, they determined that the reduction of sulfur dioxide was much as 75% from the levels in the early 1980s. Nitrogen oxide emissions were reduced by about 3% in Norway from 1986-1995, and by about 10% across Europe. However, nitrogen oxides are still a concern in the acid precipitation problem because legislation targeting industry can do little to stop the pumping of nitrogen oxides into the atmosphere from automobiles currently on the road.

Source: The Upper Midwest Aerospace Consortium