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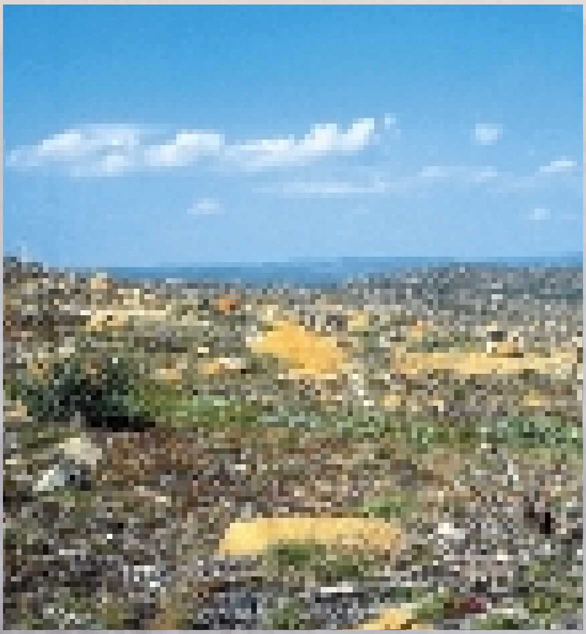

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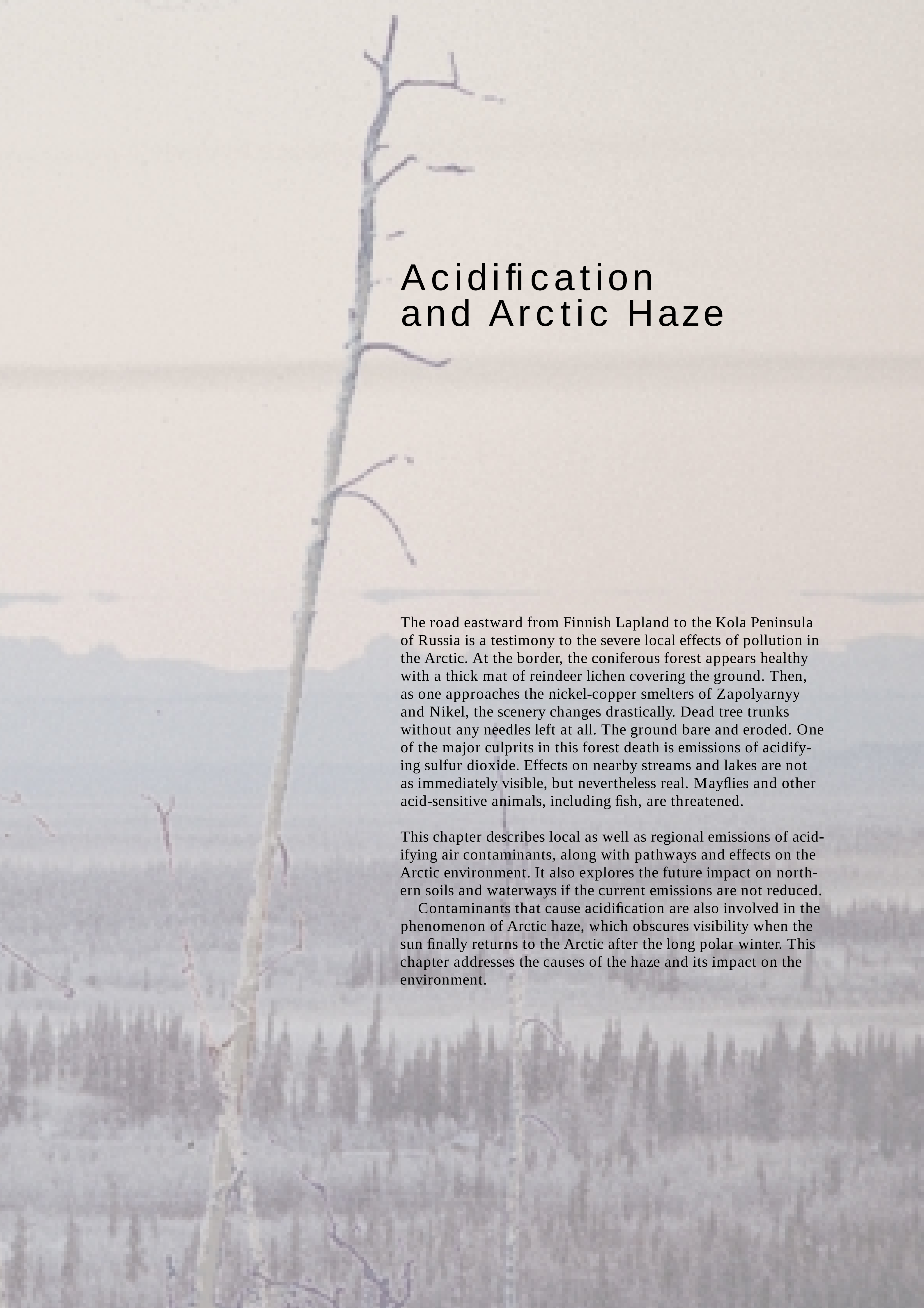
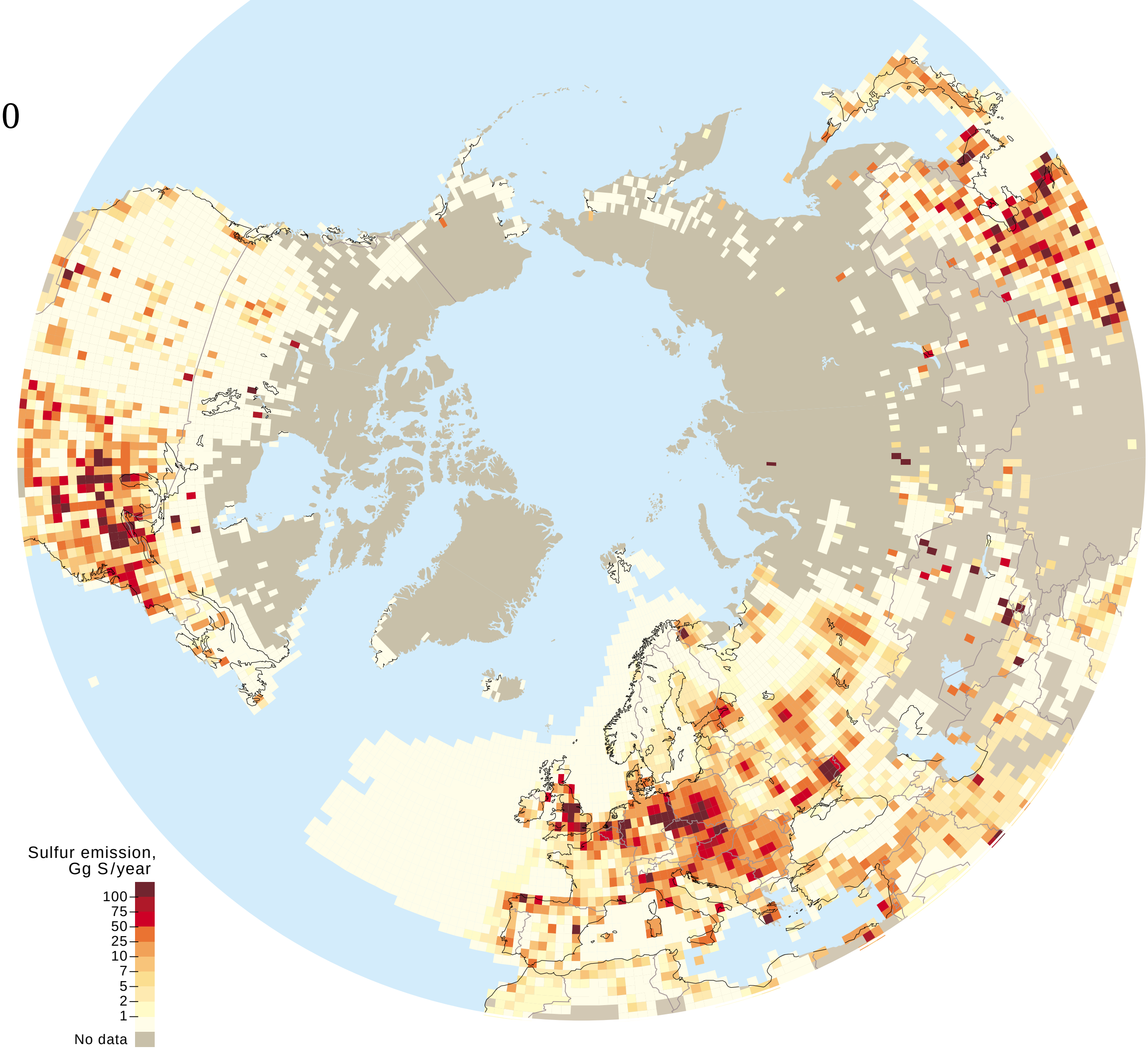


# Acidification and Arctic Haze

The road eastward from Finnish Lapland to the Kola Peninsula of Russia is a testimony to the severe local effects of pollution in the Arctic. At the border, the coniferous forest appears healthy with a thick mat of reindeer lichen covering the ground. Then, as one approaches the nickel-copper smelters of Zapolyarnyy and Nikel, the scenery changes drastically. Dead tree trunks without any needles left at all. The ground bare and eroded. One of the major culprits in this forest death is emissions of acidifying sulfur dioxide. Effects on nearby streams and lakes are not as immediately visible, but nevertheless real. Mayflies and other acid-sensitive animals, including fish, are threatened.

This chapter describes local as well as regional emissions of acidifying air contaminants, along with pathways and effects on the Arctic environment. It also explores the future impact on northern soils and waterways if the current emissions are not reduced.

Contaminants that cause acidification are also involved in the phenomenon of Arctic haze, which obscures visibility when the sun finally returns to the Arctic after the long polar winter. This chapter addresses the causes of the haze and its impact on the environment.



Emission of sulfur in the Northern Hemisphere, gigagrams (1000 tonnes) in 1985.

## Acidification – a short history

Awareness of acidification as an environmental problem has a long history. Fish kills connected to acidification were observed in Norwegian rivers as early as 1911. However, the problem did not receive international attention until the late 1960s, when similar observations were made in Sweden, Canada, and the United States. At that time, suspicions that rain was the cause were confirmed with observations of high levels of sulfuric acid in rainwater.

The surprise was the source of the acid in the rain over southern Scandinavia: most of it came from continental Europe and Great Britain. It was one of the first documented cases showing that pollutants can create havoc in ecosystems far from their sources. Scandinavia's waters suffered because its soils could not buffer the acid as effectively as soils closer to the pollutants' sources. This new scientific understanding had immediate political implications, serving as the starting point for international negotiations about controlling substances that undergo long-range transport. Pollution had become a regional rather than a local problem.

Since the 1960s, the acidification question has widened. Today, the focus is not only on streams and lakes but also on vegetation and on interactions between acidifying contaminants and other factors, such as ground-level ozone, eutrophication, and climate change. As a result of the intense scientific and environmental policy work on acidification, the sources of acidifying contaminants are fairly well understood, as are the atmospheric processes that govern their transport.

## Sources

Oxides of sulfur are the major acidifying compounds in the Arctic. They are formed when fossils fuels burn and when sulfide ores are smelted. Release of sulfur dioxide to the environment has risen with the growth in energy demand and industrial activity.

### *Industrial areas farther south contribute to Arctic air pollution*

Most sulfur in Arctic air comes from industrial areas further south. Eurasia (40 percent) and eastern North America (20 percent) are the major global sources. A large part of the remaining global emissions occur in the Far East, particularly China. The map above indicates the geographical distribution of sources.

KNUT BRY

Emissions of sulfur dioxide have decreased considerably in North America and Europe after a peak in the late 1970s and early 1980s. This results from an interplay of political decisions to cut emissions, the replacement of 'dirty' fuels, and new technologies for removing sulfur from fossil fuel and for cleaning flue gases in power plants. Nonetheless, power generation and smelting remain major sources.

### *Metal smelters have the largest emissions within the Arctic*

Production of copper, nickel and other nonferrous metals from sulfur-bearing ores create the largest emissions of acidifying substances within the Arctic. The traditional smelting method roasts the ore to remove the sulfur as sulfur dioxide and to oxidize the iron in the ore before further smelting and refining. The sulfur dioxide can be recovered in modern smelters and used as a raw material for producing sulfuric acid, gypsum, and some other inorganic chemicals. However, this is economically feasible only when the smelters are close to other industries.

Most smelter emissions come from the Nikel, Zapolyarnyy, and Monchegorsk complexes on the Kola Peninsula and from Norilsk in northwestern Siberia. Compared with similar industries in other areas, emissions from these smelters are extremely high. Norilsk is the largest source, spewing out more than a million tonnes of sulfur every year.

Sulfur emission from the smelters on the Kola Peninsula and Norilsk, Russia in 1992, gigagrams (1000 tonnes).

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The old nickel smelter, Norilsk.

### *Local energy production is a small source*

Emissions from energy production in the Arctic are generally low because the population is sparse. There are coal-fired power plants in Vorkuta and Inta in Russia, serving local settlements around coal mines and gas fields in the area. The mining settlements on Spitsbergen also have coal-fired power plants.

Shipping and fishing fleets are also sources of sulfur. The extensive fishing fleet in the Barents Sea uses large amounts of diesel fuel. Marine transport, particularly of timber and timber products, is important along the Siberian coast and on Siberian rivers.

### *Algae and volcanoes are natural sulfur emitters*

Oceans are a source of sulfur to the atmosphere in the form of dimethyl sulfide (DMS) produced by algae. Globally, they contribute 15-30 million tonnes of sulfur per year, most of it during the peak productive season. This is of the same magnitude as anthropogenic emissions from Europe. In the Arctic, the peak in DMS production is between June and August. Marine sulfur may account for as much as half of the sulfur in the air over Spitsbergen during the summer peak. On a yearly basis, however, the marine share is only 2 percent of the total.

*Sulfur dioxide turns into haze and acid precipitation*

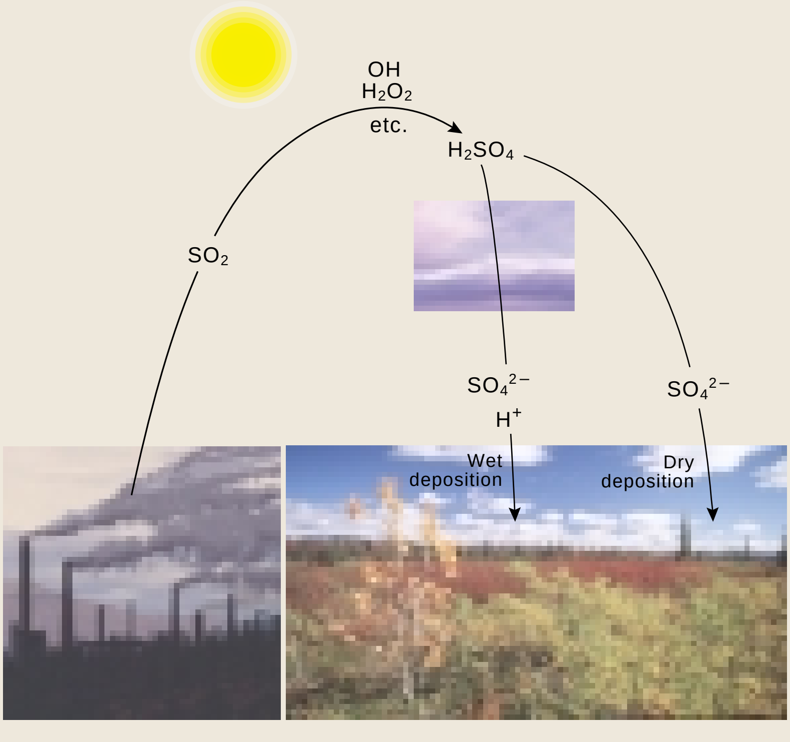
Fossil fuels with high sulfur content produce sulfur dioxide when they burn. In the atmosphere, the gas reacts with hydroxyl radicals (OH), ozone, and peroxide ($H_2O_2$), creating sulfuric acid ($H_2SO_4$).

In the cold air of the High Arctic, sulfuric acid takes the form of sub-micrometer particles, which are the main components of Arctic haze. Sulfate particles can adhere directly to surfaces as dry deposition.

Sulfuric acid can also react with water in rain, snow, and fog, dissociating into hydrogen and sulfate ions, which get washed out as wet deposition.

Biogenic sulfur compounds, such as dimethyl sulfide (DMS) from plankton and hydrogen sulfide ($H_2S$) from volcanoes, enter the same chemical cycle in the atmosphere via a reaction with hydroxyl radicals (OH).

The rates of different chemical reactions in the sulfur cycle depend on energy from the sun. In the Arctic, lack of sunlight during the polar winter limits production of the hydroxyl radical, which in turn slows production of sulfuric acid from sulfur dioxide. When the sun returns in the early spring, there is a load of sulfur dioxide in the air, ready to be converted into sulfate aerosols. This photochemical mechanism explains why Arctic haze is most pronounced in March and April, after the Arctic sunrise.



Erupting volcanoes can emit considerable amounts of sulfur. For example, Mount Pinatubo in the Philippines released 7.8 million tonnes when it erupted in 1991. On average however, volcanoes contribute an order of magnitude less sulfur to the global atmosphere than do the oceans. While the Arctic has several active volcanoes, in the North Atlantic, in the Bering Sea, and in southern Alaska, volcanoes generally emit to the upper atmosphere and do not contribute to local acidification.

An interesting local source of sulfur is the Smoking Hills in Canada, where emissions from natural combustion of shale are high enough to damage vegetation up to 500 meters from the source. However, compared with the rest of the Arctic, the quantity of sulfur is negligible.

### *Nitrogen emissions are less important*

Burning of fossils fuels also creates nitrogen oxides. In more densely populated areas, traffic and power production are the most important sources. Emissions increased rapidly from the 1950s to 1975. In North America and Europe, they have remained fairly constant since 1980. Nitrogen oxides contribute to acidification in non-Arctic parts of Europe and North America, but are less important in the Arctic context.

## Atmospheric processes

The fate of sulfur and nitrogen emissions depends on what happens in the atmosphere. Light, moisture, and reactive chemical compounds in the air act together to transform sulfur dioxide and nitrogen oxides into acid precipitation and into particles that can settle on surfaces they encounter. The box to the left describes the air chemistry of sulfur.

When air from mid-latitudes moves northward with its load of contaminants, it rises, forming layers of dirty air at higher altitudes. However, pollution released into the Arctic airmass tends to remain within a couple of kilometers of the ground because of temperature inversions that create a lid of cold air.

In the spring and winter, lack of precipitation in the High Arctic keeps acidifying contaminants suspended in the air. Sparse vegetation also provides for low deposition rates of particulate matter. During summer, two mechanisms keep the air cleaner: first, the northward shift of the Arctic front, away from major source regions, reduces contaminant inputs, and second, increased precipitation washes acid contaminants out of the air.

### *Air concentrations are highest around Kola and northern Fennoscandia*

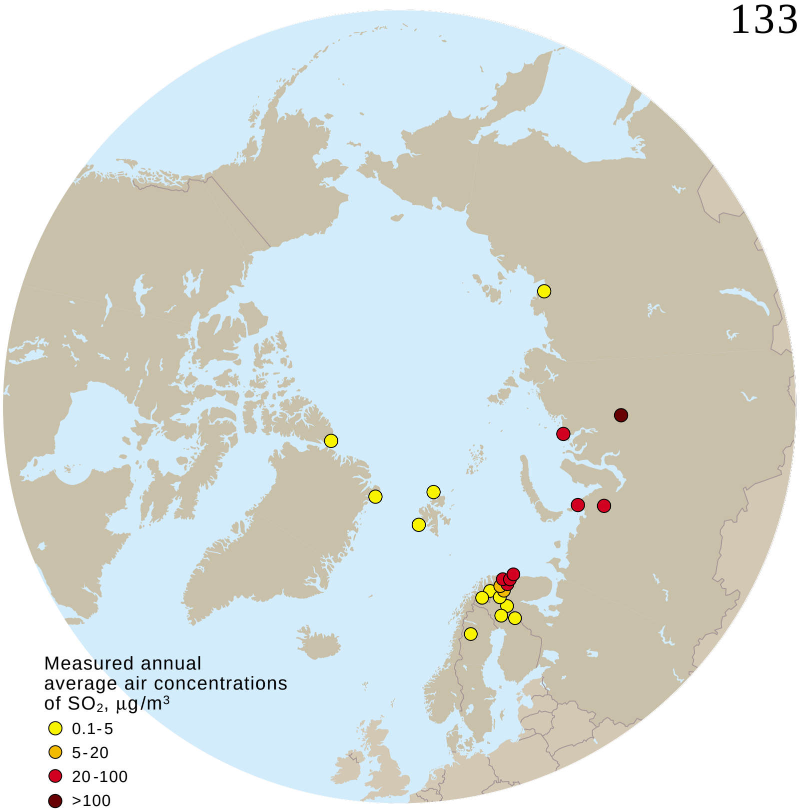
Measurements of air concentrations of sulfur dioxide show that the Kola Peninsula and northern Fennoscandia bear the brunt of European emissions that find their way to the Arctic; see the map to the right. Moreover, large local emissions in this region add to the burden, causing episodes of extremely polluted air. Peak levels are comparable to polluted regions in central Europe.

By combining detailed meteorological information with data on emissions, it is possible to make computer models of the transport, transformation, and removal of acidifying gases and aerosols. The models suggest that all sources contribute to high levels of sulfur dioxide during winter months. Only in the Kola and Norilsk regions are local sources dominant.

### *Long-term trends in emissions show up in air concentrations and glacier ice*

Emissions of sulfur dioxide from Eurasia have decreased significantly since the mid-1980s. At the monitoring station in Ny-Ålesund, Svalbard, this shows up as a decreasing trend in sulfate concentration; see the graph below. However, in the Canadian High Arctic, sulfate concentrations in air have remained almost constant. A series of measurements from Alert shows a peak every March and April, but no significant trends. This indicates that emissions within the subregions of Eurasia that affect Alert and Svalbard have changed differently.

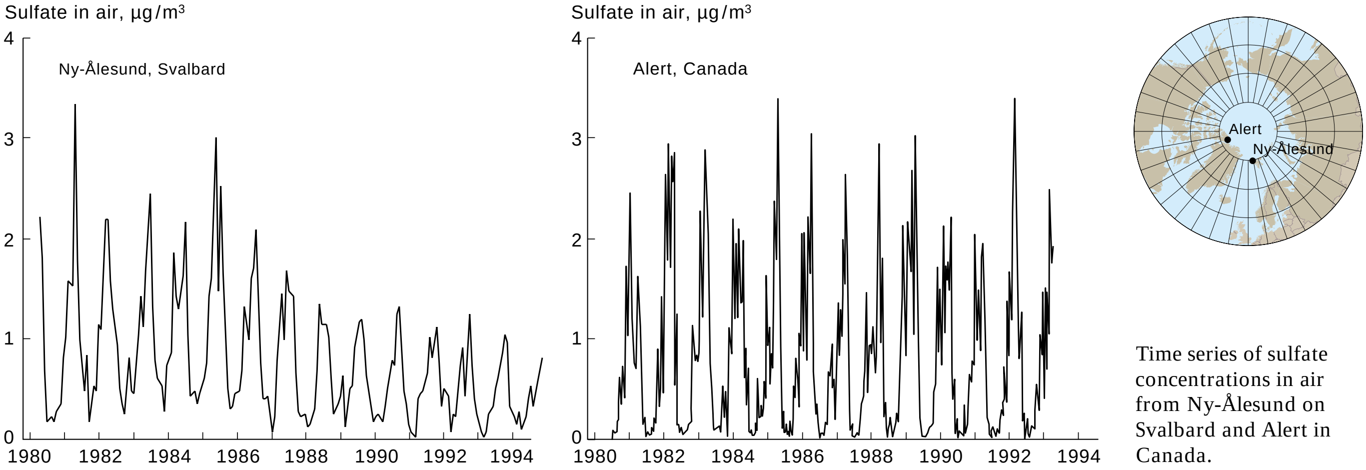
Another important source of information for assessing the development of Arctic air pollution is glacial ice. The accumulated snow, which can be analyzed in ice cores, reflects the chemistry of the atmosphere at the time of deposition. Such measurements of snow and ice composition have been made in Greenland, on northern Ellesmere Island, Canada, and on Mount Logan in northwestern Canada.



Annual average air concentrations of sulfur dioxide.

The historical record from Greenland indicates that there has been an increase in the concentrations of strong acid anions in this century, starting in the 1930s or 1950s depending on where the ice core was taken. The historical record for conductivity, which is closely correlated with acidity, indicates an increase of about 75% between 1956 and 1977. This trend mirrors European sulfur dioxide and nitrogen oxide emissions.

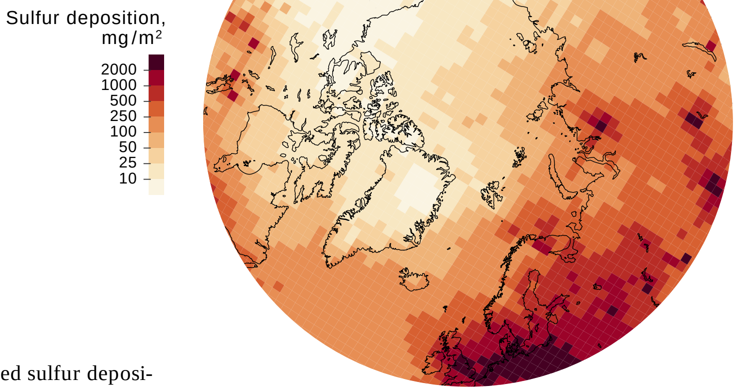
Measurements of recently accumulated ice layers indicate that the peak in sulfates and fine particles occurred at the beginning of 1980s. There were no major changes during the 1980s, but decreases were detected at some stations at the end of the decade. These recent trends can be attributed partially to documented reductions in sulfur emissions in Europe, and partially to the replacement of coal by natural gas to produce heat and electricity, particularly in the former Soviet Union.



Time series of sulfate concentrations in air from Ny-Ålesund on Svalbard and Alert in Canada.

### *Highest deposition is around the smelters*

While air concentrations are important for understanding transport of acidifying contaminants and direct impacts of sulfur dioxide on forests, data on deposition gives a better picture of the acid load on vegetation, soil, and water. Deposition depends not only on air concentration, but also on how effectively precipitation washes out acidifying substances, and on how effectively acid particles adhere to surfaces such as snow and vegetation.



Modeled sulfur deposition in 1988.

The general picture is that the sulfur deposition in northern Canada, Alaska, and Greenland is low, whereas the load in the Barents and Taimyr regions is relatively high; see the map above. The levels range from slightly above background in the low-deposition areas to several grams of sulfur per square meter in areas close to Russian smelters, which is as high as in the polluted areas of central Europe.

The most detailed information on deposition patterns comes from northern Fennoscandia and the Kola Peninsula because of concern over the fate of the large sulfur dioxide emissions from Russian smelters in the region. Emissions seem to have only a moderate influence on precipitation in areas farther than 20-50 kilometers from the smelters. Surprisingly little information is available from Norilsk, which has the largest smelters in the Arctic.

Acidifying particles can also deposit directly on vegetation, on rock surfaces, or on snow and ice rather than through precipitation. Such dry deposition is low in the Arctic because surfaces of snow and ice are relatively inefficient in gathering acidic particles and gases compared to vegetation-covered surfaces or water. However, it accounts for a high proportion of the total deposition in areas close to the sources. For example, approximately 75 percent of acid deposition on the Kola Peninsula is through dry deposition. Research into the fate of contaminants when they encounter tree canopies supports the idea that dry deposition of sulfur is the dominant pathway of acidifying pollutants into ecosystems around smelters. Beyond 150 kilometers, dry deposition contributes much less to total deposition.

## Arctic haze

The term Arctic haze was coined in the 1950s to describe an unusual reduction in visibility that the crews of North American weather reconnaissance planes observed during their flights in the High Arctic. After further study of visibility data in the mid 1970s, it became clear that the haze was seasonal, with a peak in the spring, and that it originated from

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Arctic haze over Mount McKinley, Alaska.

anthropogenic sources outside the Arctic. The most severe episodes occur when stable high-pressure systems produce clear, calm weather. Visibility can be reduced to 30 kilometers, in spite of the otherwise clear weather. Matthew Bean, a Yupik Eskimo elder from Bethel, Alaska, describes the changes he has seen in the sky: 'Sometime back, the skies on a clear day used to be deep blue all over, even at the horizon. Now you hardly ever see that anymore, especially on the horizon. It is always pale blue, almost white or even dirty gray. It makes me sad to see what future generations are going to have to put up with.'

### *Haze aerosols are mainly sulfate*

The haze has been thoroughly analyzed. It consists of sulfate (up to 90 percent), soot, and sometimes dust. The particles are about the same size as the wavelength of visible light, which explains why the haze is so apparent to the naked eye. The composition of haze has been used as a chemical fingerprint to identify its sources. The presence of black carbon and a particular relationship between the metals vanadium and manganese indicate coal burning. Most of the particles originate in Eurasia.

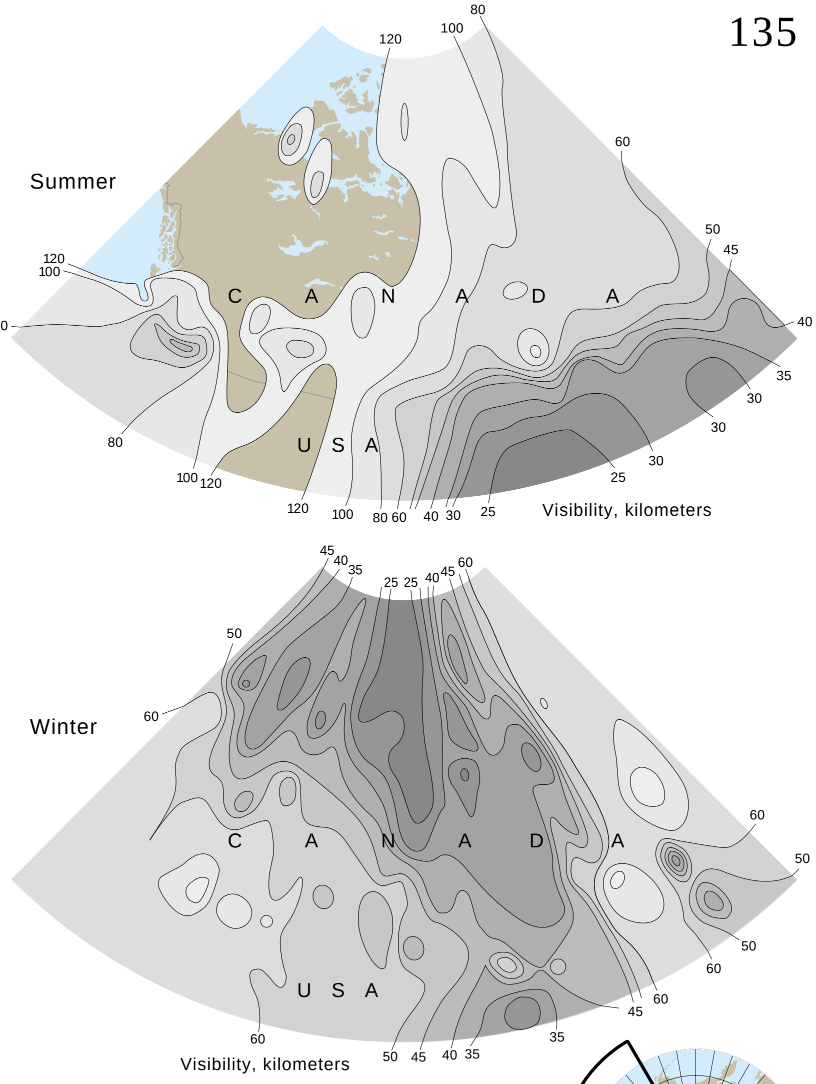
The transport routes for the haze are well understood. Eurasian emissions are much more important than those from North America, in part because the Eurasian sources are 5° to 10° further north than those in North America. Moreover, the Arctic air mass stretches relatively far south over the Eurasian landmass during the winter. The contaminants are thus picked up by the airmass that moves northward and over the pole in winter months.

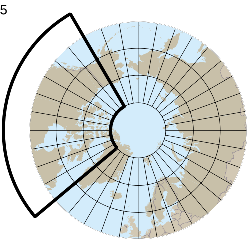
### *Winter blocking favors transpolar transport*

Why is Arctic haze important? First, it completely changed the earlier notion that aerosol pollution could only be local or regional. The cold, dry air in the polar regions allows particles to remain windborne for weeks rather than days, which in turn allows sulfur contaminants to spread from industrial sources in Eurasia across the entire Arctic and into North America.

Second, haze particles might give metals and other contaminants a free ride to and within the polar region. Metals as well as some persistent organic compounds adhere to aerosols and could be deposited along with the aerosols Substantial amounts of industrial contaminants may thus be washed out by precipitation occurring over major ocean areas surrounding the Arctic.

Arctic haze often appears in distinct bands at different heights because the warm dirty air is forced upward until it reaches the dome of cold air that sits over the North Pole in winter. The clear, cold winter weather is one important reason why Arctic haze occurs in winter and spring and not in summer and fall.

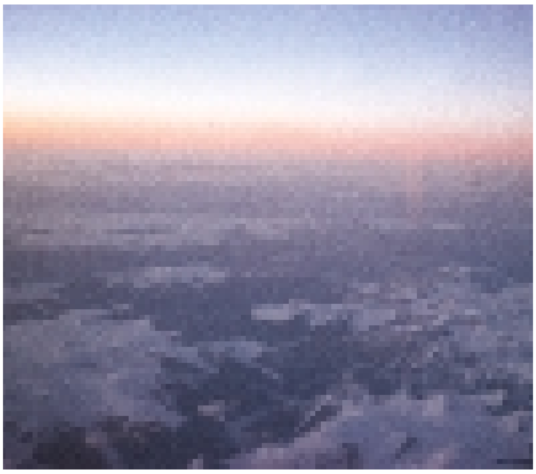




Summer and winter visibility in North America showing the effects of Arctic haze in winter.

The most apparent effect of the haze is that it reduces visibility. The figure above shows how severe the situation can be in different parts of Canada, but the phenomenon occurs throughout the High Arctic. The haze has previously been considered a hazard to air traffic, but today's automated navigation systems have made poor visibility less of a problem.

In spite of their impact on visibility, the levels of sulfur compounds are much lower than those found in heavily polluted cities. Due largely to low deposition rates, the haze causes neither adverse effects on plants and animals, nor direct health problems in people.



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Arctic haze over Greenland

### *The haze absorbs and scatters solar energy*

Recently, Arctic haze has also been brought into discussions on global climate change. Unlike regions with low surface reflectivity, acidic and soot-laden aerosols over highly reflective snow tend to warm rather than cool the spring Arctic atmosphere. At certain times of the year, a viewer from space would see the North Pole as orange-brown rather than white because of the soot in the haze. The consequences for global climate are poorly understood and climate models are just starting to take the haze into account. They suggest small but measurable effects.

## Levels in soil and water

The impact of acid deposition on soils and freshwater ecosystems depends to a large extent on whether acid precipitation has an opportunity to percolate through the soil, and if so, on the type of soil in that area. Soil chemistry has been extensively studied during past decades, and the emerging picture explains why the same acid deposition has little effect in some areas and severe consequences in others.

### *Poorly buffered soils are sensitive to acidification*

In waterlogged areas of the tundra and in many areas with permafrost, the soil consists mainly of peat. These soils are naturally acidic. The high content of organic matter means that they are strongly buffered and therefore resistant to acidification by airborne contaminants, at least at moderate levels of deposition.

*pH and buffering capacity*

Acidity is measured as pH, which indicates the concentration of hydrogen ions ($H^+$) in a solution. At pH 7, a solution is neutral, meaning that the concentration of $H^+$ is equal to the concentration of hydroxyl anion ($OH^-$). Below pH 7, $H^+$ dominates and a solution is acidic.

pH is a logarithmic function, and each step in the scale is a tenfold change in acidity. If the pH in a lake has decreased from 7 to 6, the acidity has increased ten times, if the pH has changed from 7 to 5, the acidity is one hundred times higher, and so on.

The sensitivity of soils and lakes to acid precipitation depends to a large degree on processes that resist acidification. Weathering of basic minerals neutralizes incoming acidity and provides base cations for buffering cation exchange. Over time this buffering capacity can be exhausted if the rate of acid deposition is higher than the geological production of new base cations, resulting in a very rapid drop in pH. Measuring the share of base cations from the overall cation exchange capacity, i.e. base saturation, gives an estimate of the present status of soil acidification and sensitivity to further acidification.

The analogous sensitivity of water to acid deposition is expressed as alkalinity. A lake with high alkalinity has a high ability to resist changes in pH.

Mineral soils are low in organic matter and can be much more sensitive. Their reaction to acids depends to a large extent on the weathering rate of the parent material. In many areas of the Arctic, glaciers removed all the soil and most of the weathered material, leaving only relatively inert silicate-rich rocks, many of which have a low capacity to supply base ions. Locally, however, carbonate minerals create soils that are fairly resistant to acidification, because they supply base ions at a high enough rate to neutralize the acid.

Clay content of soil is also important. The fine particles of which clay is composed have a large surface area, which increases the soil's capacity to buffer acidic water. A high content of organic material can have the same effect. Coarse soils, on the other hand, often let the water through too fast for effective buffering.

The figure on the opposite page highlights the areas that are sensitive to acidification. They include most of northern Fennoscandia, the northern Kola Peninsula, and non-carbonate rocks and coarse-textured shallow soils on the Canadian Shield. The area around the Severonickel and Pechanganikel smelters on the Kola Peninsula have basic or ultrabasic rocks, with a high buffering capacity. Many of the islands of the Canadian Archipelago also have acid-resistant soils.

The rate at which the acidic water percolates through the soil will determine whether the buffering capacity will be fully used. If most of the water comes during a short period, as is common during the snowmelt season, it will run directly into streams and lakes rather than through the soil. In the Arctic, percolation through the soil can also be inhibited by permafrost.

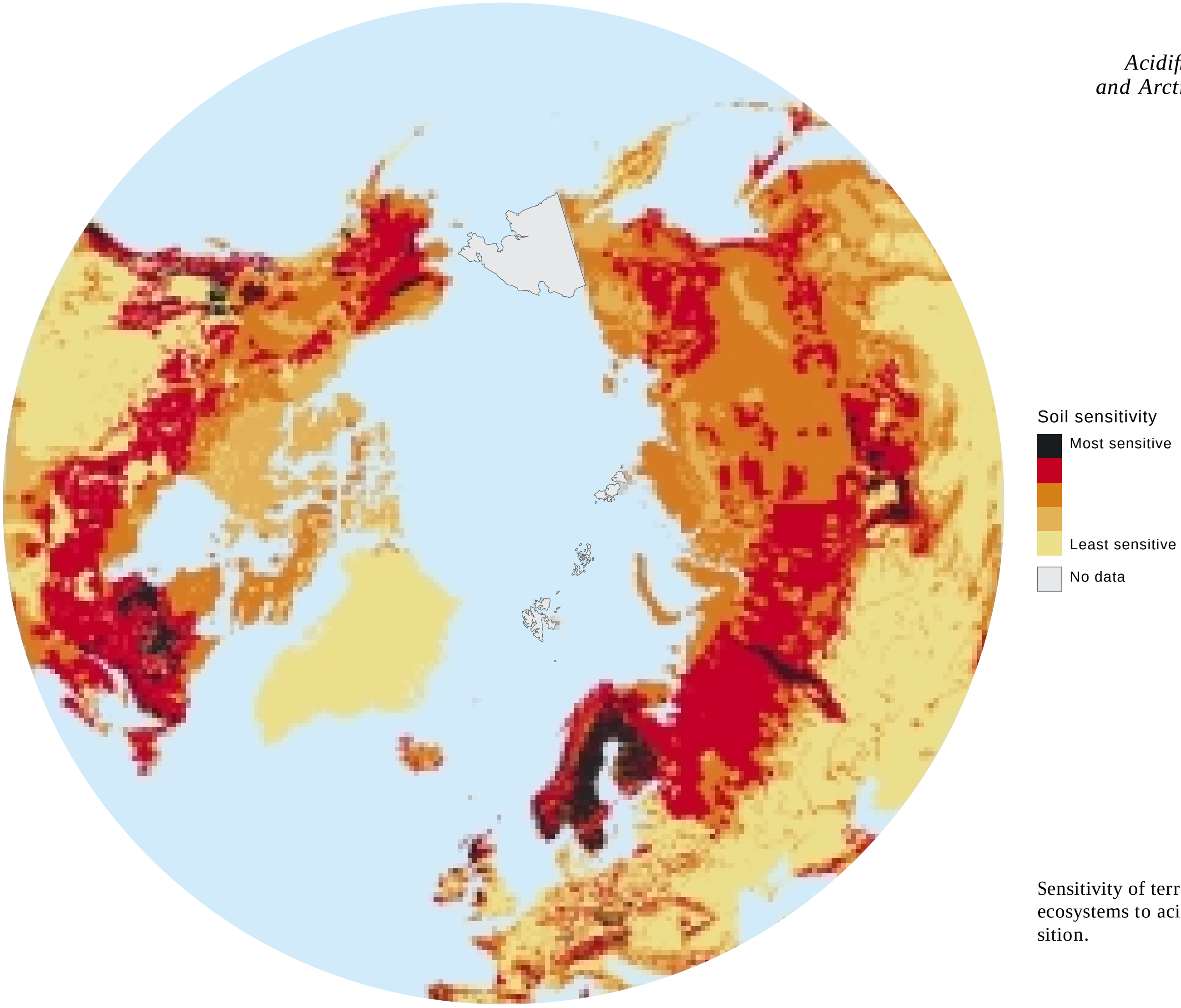
### *Soil damage is limited to vicinity of smelters*

The only evidence for soil acidification in the AMAP area comes from the immediate vicinity (0 to 30 kilometers) of the nickel-copper smelters on the Kola Peninsula. In these areas, base saturation levels, i.e. the amount of basic cations available for buffering, can be as low as 15 percent. The base cations in the soil have probably been replaced by high loads of hydrogen ions and heavy metals.

In northern Fennoscandia and other parts of northwest Russia, base saturation levels range from 15 to 80 percent. Theoretical calculations suggest that the sulfur deposition load in some parts of northern Fennoscandia exceeds the critical load for forest soils. However, the actual sulfur concentration in the humus is only slightly elevated, and there are no signs of accelerated soil damage due to acidification in the northernmost parts of Finland, Norway, and Sweden.

A major concern with acidified soil is that the low pH will allow aluminum to leach out, but the maximum reported total aluminum concentration in ground water, 2 milligrams per liter, is well below the threshold value for the onset of aluminum damage to roots. The high organic matter content of the podzol soils of this area also means that a large portion of the available aluminum is in a form that is not toxic to plants.

There is no information about the soil around Norilsk. In Chukotka and on Wrangel Island, base saturation levels are very high.



Sensitivity of terrestrial ecosystems to acid deposition.

The predominance of high base saturation levels in Arctic and subarctic soils means that at present deposition rates, it will take some time before the buffering capacity of most areas is exhausted and the effects of acid deposition become apparent.

## *Running water is vulnerable to acid pulses*

The effects of acid deposition on lakes and streams depends on whether the runoff has percolated through buffering soils and on the time allowed for buffering reactions to occur in the lakes and streams themselves.

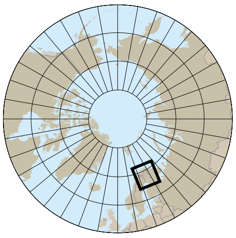
Similar to soils, lakes have a buffering capacity that can be depleted by excess acid inputs. Whether and how quickly such depletion occurs depends on the size of the reserve (alkalinity) and how long the water stays in the lake. Acidification can thus also be described as a loss of alkalinity, similar to the loss of base cations in soils. Lakes have some ability to counteract the loss of alkalinity. Microorganisms that process sulfates and nitrogen also release calcium, magnesium, and potassium from lake sediments, restoring some alkalinity. This repair potential depends on the rate at which sulfates, nitrates, or other anions are available.

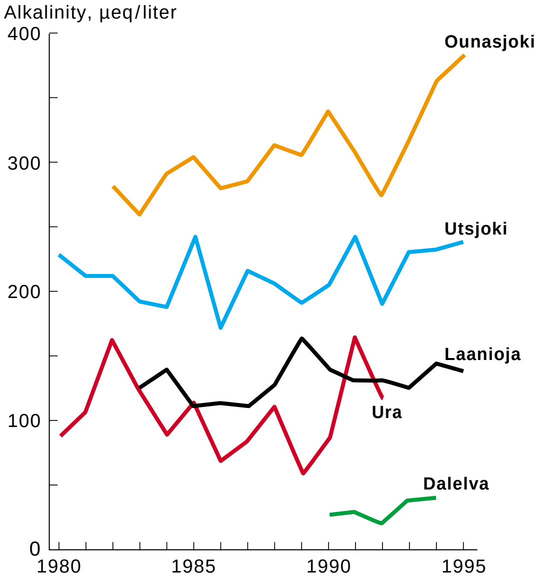
During snowmelt, streams can be more sensitive to acidification than lakes, because the runoff water filling the streams carries the acid load gathered in the snow throughout winter. This situation is exacerbated because most acids in the snow are released at the beginning of the spring melt. Often, the first 20 percent of the meltwater contains up to 80 percent of the major acidic cations, increasing the average concentration by a factor of four. Early meltwater seldom percolates through the soil, since the ground is still frozen, but flows directly into the streams in the catchment area. Even in low deposition areas, such acid pulses can have a pH below 5.5. During later snowmelt, the quality of the meltwater usually improves as most acidifying compounds have already washed out.

### *Critical loads tell about sensitivity*

How much acid deposition can the soil and water in a catchment area handle before acidification will affect plants and animals in the long run? The answer to this question is summarized as the ‘critical load’. The critical load depends on how effectively and how fast the soil and water chemistry can resupply the base ions that neutralize the deposited acid. If the input of sulfuric acid is faster than the regenerating processes, the soil and water will slowly but surely become more acidic. The critical load of acidity is exceeded when the calculations show that the pH will eventually drop far enough to affect plants and animals.

Critical loads have been calculated and mapped for Europe and are used as a basis for political negotiations about reducing acidifying emissions under the auspices of the Convention on Long-range Transboundary Air Pollution (LRTAP).





Time trends for alkalinity in some rivers and streams in northern Fennoscandia and the Kola Peninsula, microequivalents per liter.

### *Streams and rivers reflect proximity to smelters*

The figure above shows some of the time trends in acidification of the waterways in northern Fennoscandia and the Kola Peninsula.

In northern Norway one might expect acidification of rivers close to the nickel-copper smelter at Nikel. In the river Jakobselva, sulfate concentrations are indeed high with a marked decrease in alkalinity in the spring, but not elevated enough to cause acid water. The river Dalelva, on the other hand, clearly suffers from acidic pulses during the spring flood. For instance, during the spring of 1990, its pH dropped from 6.2 to 5.0 in just one day when the snow started melting. A comparison of annual average values shows that the quality of water here has improved during the past few years.

The rivers of the Kola Peninsula have suffered a significant decrease in alkalinity, and some streams have had severe acid pulses. On an annual basis, there is some indication of a slight recovery of alkalinity in recent years.

The results of Finnish monitoring of river water chemistry show that acidification of the water has leveled out. Since the 1970s, there has been no decrease in pH. Moreover, the buffering capacity has remained high, and alkalinity has increased between 1980 and 1995.

Measuring sulfate content provides another indication of how waterways respond to changing deposition. In the western parts of Finnish Lapland, which are influenced more by emissions from outside the Arctic than from the Kola Peninsula, there is a slight decrease, reflecting the decline in emissions. In northeastern Lapland, the concentrations are more stable.

The rivers in northern Sweden mirror the decrease in European emissions, with sulfate concentrations decreasing since the late 1970s. The buffering capacity is largely unchanged. However, in many small streams there is a decline in animals that are sensitive to low pH. The annual average pH of these streams is above 6, but the damage may be caused by the brief acid pulse from the first days of snowmelt.

### *Many lakes are acidified or susceptible*

Small lakes are sensitive to changes in water chemistry and are therefore used for monitoring acidification. One of the hardest-hit areas in the Arctic appears to be Sør-Varanger, Norway. Some of the lakes have no alkalinity left, and almost half the lakes have a pH of less than 6.0. Since 1986, however, there has not been any further acidification. Recently, the concentrations of some buffering ions in lakes east of Kirkenes and in the Jarfjord region have even increased, which could be a first sign of recovery from acidification.

There are acidified lakes throughout the northern Kola Peninsula, and strongly acidified lakes in the mountains of the Kiopukas, Chuna, Volchii, and Monche regions. Northward from Pechenga along the Barents Sea coast, the condition of the lakes is critical.

The lakes of northeast Finland have lost much of their buffering capacity. In the most sensitive areas, northeast of Lake Inari, some lakes have no alkalinity left. Map ‘A’ opposite shows the status of lake acidification in the Fennoscandian Arctic and the Kola Peninsula.

The lakes in the AMAP region of Canada have not been acidified to any significant extent. Some lakes with extremely low pH seem to have been unproductive throughout their existence because of natural acidification. Data from Prudhoe Bay in Arctic Alaska also do not indicate any acidification. However, some small ponds in the Arctic National Wildlife Refuge have low alkalinity and poor buffering capacity and would therefore be susceptible to acidification.

Map ‘B’ opposite shows the critical load of sulfur for Arctic lakes. The critical load varies geographically, with values ranging from 300 to 1300 milligrams sulfur per square meter per year.

The largest area where the critical load is currently exceeded is in northern Finland, Norway, and the Kola Peninsula. In Sør-Varanger, 70 percent of the area cannot buffer current depositions, most of which come from emissions on the Kola Peninsula. On the Kola Peninsula itself, the critical load is exceeded in almost half of the area.

### *The groundwater has not suffered yet*

Groundwater benefits from the capacity of soil to buffer acidic surface water. In Finland, there are no signs that acidification is taking place. At a groundwater station near the Finnish-Russian border, at Nellim, there has been no appreciable change in alkalinity or pH during the 15-year monitoring period.

Also, in inland Norway and northern Sweden, the groundwater has not been affected by strong acids, nor has there been any continuous groundwater acidification.

## Effects on plants and animals

When the levels of sulfur dioxide in the air are high enough or when soil and water have been severely acidified, plants and animals will suffer. Such visible deterioration of the environment is well documented in the vicinity of large smelters.

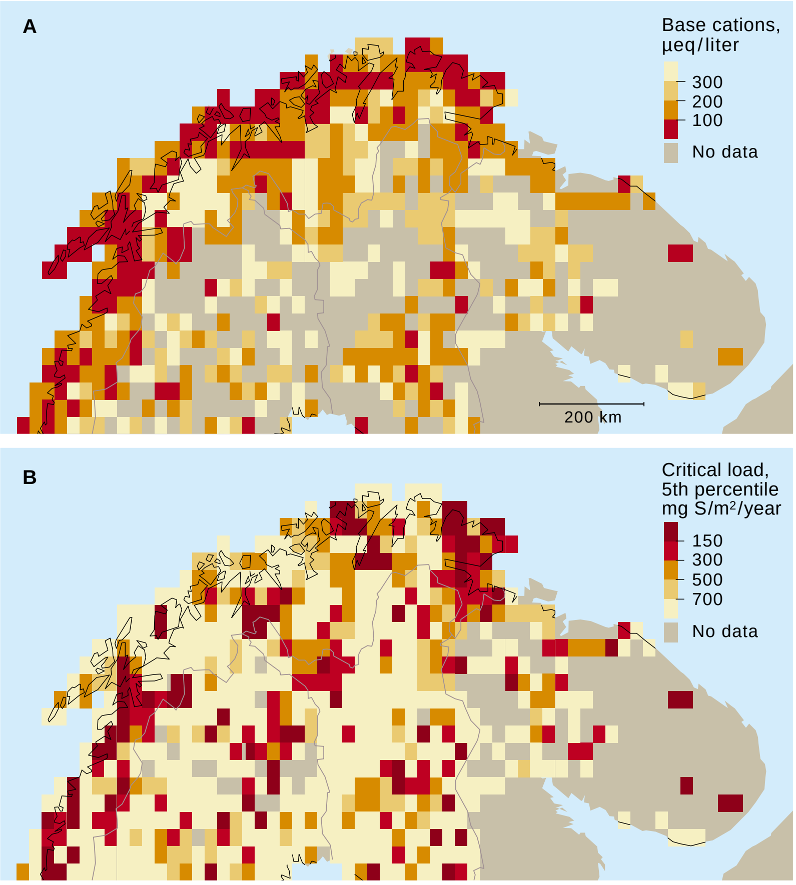
### *Loss of soil fertility contributes to tree death*

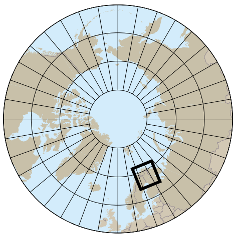
Soil fertility depends on the availability of nutrients. In upland soils, nitrogen is often a limiting factor for tree growth, and on peatland, phosphorus and potassium are usually in short supply. Acid deposition in the form of nitrogen compounds can increase soil fertility in the short term, but acidification will eventually deplete soils of many of their nutrients.

Neither soil-chemistry analysis nor investigation of the nutrients in tree needles indicate any loss of soil fertility in northern Fennoscandia.

Close to the smelters at Monchegorsk and Nikel on the Kola Peninsula, there is a severe decrease in soil fertility caused by high inputs of nickel and copper, which have replaced nutrient ions. The levels of several macronutrients and trace elements are extremely low, both in the soil and in tree needles, and the poverty of the soil has undoubtedly contributed to tree death in the area.

Fungi and microorganisms help maintain soil fertility by breaking down plant matter into humus. Studies of areas close to the Pechenga nickel-copper smelter show that the number of species has decreased and that these decomposer communities are now dominated by acid-resistant species. While it is difficult to separate the effects of acidification from the effects of heavy metals, the result of the combined stress is dramatic. In the area closest to the smelters, the humus layer has completely disappeared.





A: Base cation concentrations in lakes in northern Fennoscandia and the Kola Peninsula, microequivalents per liter.
B: Critical load of acidity reflecting the load of sulfur deposition the lakes can tolerate without harmful effects.

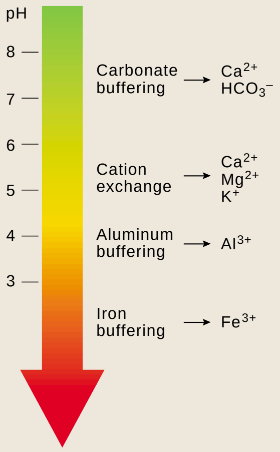
### *Sulfur dioxide has damaged the forest*

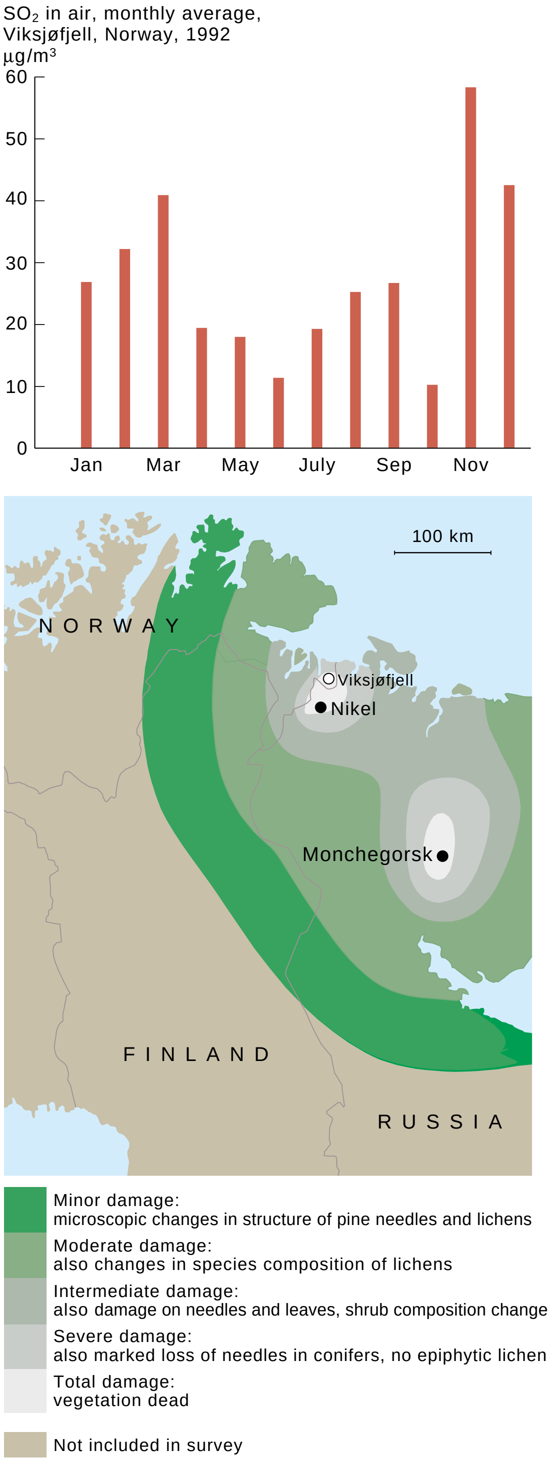
Aside from its acidifying effect on the soil, sulfur dioxide can harm plants directly. If the levels in the air are high enough, needles and leaves are damaged. At lower levels, acid deposition stresses plants, making them more vulnerable to diseases and harsh weather.

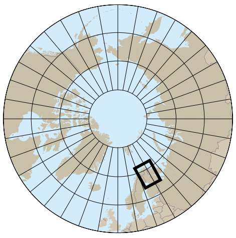
The critical level of sulfur dioxide for forest ecosystems at low temperatures is an annual average of 15 micrograms of sulfur dioxide per

*Box: Acidification depletes nutrients*

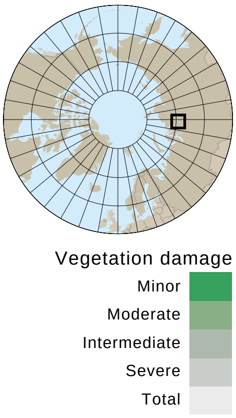
Most Arctic mineral soils are naturally acidic, because slow weathering limits the rate at which they can replace the base ions that trees use for nutrients. Acid deposition amplifies this natural acidification process when hydrogen ions replace base ions, causing the base ions to leach further down into the soil or to be washed away in runoff. As a result, the pool of nutrients in the soil decreases. Moreover, once the easily available base ions such as calcium and magnesium are used up, another buffering process starts freeing previously bound aluminum ions, which are toxic to plants. Tree damage from acidification has many causes, but the lack of nutrients and the excess of aluminum ions are two important culprits. The figure shows the pH at which different base ions become mobile.

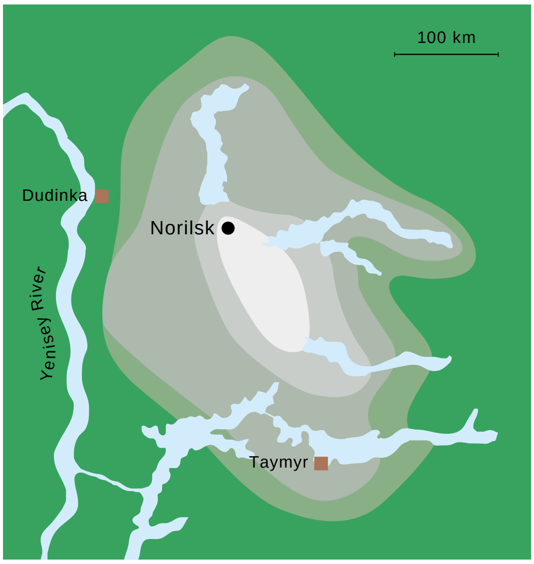






Sulfur dioxide concentration in air, monthly averages, Viksjöfjäll, Norway, 1992, and extent of vegetation damage on the Kola Peninsula.





Extent of vegetation damage around Norilsk, Russia.

cubic meter of air. The vegetation can withstand higher levels for short periods, and the critical level for a one-hour exposure is 150 micrograms of sulfur dioxide per cubic meter of air.

Both long-term and short-term critical values are exceeded over large areas of the Kola Peninsula and on the Norwegian side of the Norway–Russia border. At Viksjøfjell in Norway, there have been hourly mean concentrations of 3000 micrograms per cubic meter. The concentrations are occasionally higher than 1000 micrograms per cubic meter as far as 50 kilometers from the Nikel smelter.

Sulfur dioxide has damaged a vast area around the smelters. The figure to the left indicates the extent of the damage around Nikel and Monchegorsk and the accompanying levels of sulfur dioxide in the air. Close to the smelters, the forest is completely dead. The Monchegorsk forest-death area, caused by emissions of sulfur and heavy metals, covers 400-500 square kilometers and extends 10 kilometers south and 15 kilometers north of the smelter complex. This zone is expanding at a rate of half a kilometer per year. The areas severely affected by air pollution around Nikel-Pechenga and Varanger increased from 400 square kilometers in 1973 to 5000 square kilometers in 1988.

The prevailing winds carry most pollutants from the Nikel and Zapolyarnyy smelters to the northeast and east. The forest-death area caused by these smelters is greater in size than the one near Monchegorsk.

The outer visible-damage zone extends into the eastern parts of Inari in Finland, which is the only Finnish area under immediate threat from air pollution from the smelters. On the Norwegian side of the border with Russia, the main problem seems to be episodes of high air concentrations of sulfur dioxide. On several occasions, this has damaged trees and other vegetation, causing leaves and needles to turn brown. The most severe vegetation damage on the Norwegian side of the border is around Jarfjord Mountain.

The figure at the bottom of the page shows the area around Norilsk that has been damaged by sulfur and heavy metals from the nickel-copper smelters. This zone extends about 80 kilometers south of the city.

### *Kola emissions have killed lichens and some shrubs*

Most vegetation in northern Norway and the Kola Peninsula is lichens and dwarf shrubs. Lichens, in particular, are very sensitive to air pollution, and the high sulfur dioxide load has had a devastating effect. Between 1973 and 1988, the lichen-dominated area around Nikel-Pechenga and Varanger decreased from 2783 square kilometers to 538 square kilometers. Lichens growing on birch trunks are

KNUT BRY

Cemetary, Norilsk.

absent in large parts of the Norwegian forest close to the Russian border.

The growth of reindeer lichen is especially important as it provides reindeer populations with winter fodder. In fact, the carrying capacity of the most important ranges of reindeer is determined by the growth of this lichen. Close to the smelters, reindeer lichen has completely disappeared. Only 50 to 60 kilometers away from the smelters, lichens continue to grow at their normal rates.

Dwarf shrubs have an important ecological role in protecting the ground from erosion. In areas with forest death, they are often the only remaining field vegetation. The proportion of blueberry shrubs has decreased near the emission sources, whereas another shrub, crowberry, has increased. Some species of moss can also benefit from high sulfur dioxide concentrations.

KNUT BRY

90 km from Norilsk, Russia.

KNUT BRY

Near Monchegorsk, Kola Peninsula, Russia.

FREDRIK EDSTRAND

Vegetation in the crystal-clear water of an acidified lake.

### *Sensitive invertebrates have disappeared*

Streams and small lakes are more sensitive to acidification than larger water bodies, and their plants and animals are thus likely to suffer the consequences sooner. The diagram on the opposite page shows the pH at which various aquatic animals will disappear. On the Kola Peninsula, there has been a decline in the diversity of plankton as acid-sensitive species have disappeared. In small acidified lakes, the number of species and the abundance of phyto- and zooplankton are as low as in lakes contaminated by heavy metals. In the Jarfjord region of Norway, a number of acid-sensitive daphnids, a group of small crustacean plankton, have disappeared.

The bottom fauna of streams have also suffered in this region. A study of the Sør-Varanger and Varanger areas showed that sensitive species were missing and the total number of species was low. In the Jarfjord region, acid-sensitive mayflies have disappeared from acidified lakes, and in the Dalelva watershed the bottom fauna are damaged because of low pH and high aluminum concentrations.

Also in the Murmansk region, many acid-sensitive species have been lost, and the number and diversity of animals in the bottom sediments are low. The worst effects are seen in remote lakes on base-poor bedrock.

In northeastern Finland, bottom-dwelling fauna have fared better. No clear indication of acidification effects in streams and rivers has been detected so far, and even acid-sensitive species, such as mayflies and caddis flies, are still present. Since acidification increases from west to east, it is possible that the lakes closest to the Russian border might be affected.

### *Spawning water are acidified enough to affect brown trout*

The rivers in the northern part of the Kola Peninsula and Sør-Varanger are important for fish production, especially for brown trout and Atlantic salmon. The salmonid fishes are especially sensitive to low pH during hatching, as fry, and later on in the life cycle as smolts. In small streams, pH values during snowmelt are low enough to be harmful to the fish, especially if metal levels are high. Brown trout is most vulnerable and possibly threatened at current spring-time water quality levels.

Salmon have done better, probably because they spawn in larger rivers that are not as easily acidified. In addition, salmon egg hatching also takes place at a more favorable time. Arctic char also seem to be less affected than brown trout, probably because they spawn in lakes rather than streams. Interviews with fishermen do not suggest any severe loss of fish in the fresh waters of the county of Nordland in Northern Norway.

BJØRN OLAV ROSSELAND

Spawners of Atlantic salmon killed during an autumn episode of toxic acidic waters.

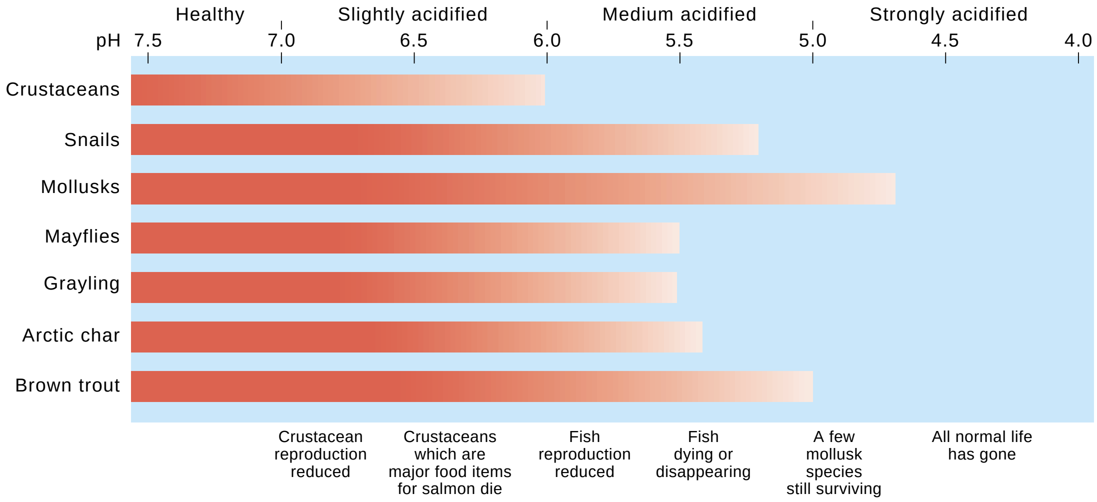
BJØRN OLAV ROSSELAND

Smolts of Atlantic salmon killed during an acidic episode caused by snowmelt in spring.

In small lakes in northeastern Finland, even acid-sensitive species have not been affected by the acidification. Burbot, European minnow, and brown trout are still abundant.

### *The future hinges on reduced emissions*

How will Arctic ecosystems fare in the future if emissions of acidifying compounds continue? One way to answer this question is to



Sensitivity of different organisms to decreasing pH.

make models of how soils and water respond to different emission levels. Such models for the river Dalelva in northern Norway and the Christmas Lakes in northeastern Finland suggest that, in the long run, the region is vulnerable even to fairly low rates of sulfur deposition. The models indicate that future sulfur deposition will have to be very low to stop and reverse the acidification now taking place.

If there are no reductions in emissions, the models predict that the Christmas Lakes will rapidly acidify after 2010. A new steady-state will be achieved after some 40 years, at a pH of around 4.5. In the river Dalelva, the high emission scenario, which assumes no reductions from current levels, is predicted to result in water at pH 5.5 or less by 2040.

On the positive side, the soil base saturation levels remain fairly high. This means that a drastic reduction in sulfur deposition to background levels within 10 to 20 years would allow these waters to avoid the predicted damage.

## Summary

Acidification of Arctic ecosystems is at present a local problem around the nickel-copper smelters on the Kola Peninsula and at Norilsk in Russia. The input of sulfur dioxide into the environment in these areas is extremely high. The air concentrations and the deposition rates are comparable to heavily polluted areas in central Europe. On the Kola Peninsula, the soil in some areas is severely acidified. More information is needed about the Norilsk region.

The forest ecosystem close to smelters is completely destroyed, and the forest-death area is increasing every year. However, only restricted impacts extend into areas of Finland and Norway that neighbor the Kola Peninsula.

High deposition of sulfur affects water quality on the Kola Peninsula and in eastern Finnmark in Norway. In particular, it contributes to pulses of very acidic water in some rivers and streams during spring snowmelt. These acid pulses may be more critical to plants and animals in these waters than annual average pH. In some streams and small lakes, acid-sensitive invertebrates have disappeared. Brown trout is the most vulnerable fish species. Information from the area around Norilsk is not available. Models suggest that continued sulfur dioxide emissions can pose an even greater threat in the future. In particular, some lakes in northern Fennoscandia are vulnerable even to fairly low rates of continued sulfur deposition.

Except for the regions affected directly by the smelters (within 200 kilometers), there is no evidence for large-scale soil or water acidification in the Arctic today.

The sources of acidifying contaminants to the Arctic as a whole are well known. Sulfur dioxide from combustion of fossil fuels and smelting of sulfuric ores is most important. The major source regions are industrial areas further south in Eurasia and North America. Sulfur dioxide reaches the whole Arctic area because unique meteorological conditions allow long-range transport during the polar winter.

In the atmosphere, sulfur dioxide converts to sulfate aerosols, which can make the sky look hazy, even on clear days. In late winter and early spring, high concentrations of sulfate aerosols reduce visibility throughout the High Arctic. The aerosols have the potential to carry other contaminants. They might also have an impact on regional and global climate, but this aspect of the haze is poorly understood at present. Most of the sulfates that form Arctic haze originate from sources in Eurasia.