Air pollution, Environment and Future

30 years of research on forest, soils and water

Hans Hultberg, Svante Hultengren, Peringe Grennfelt, Hans Oscarsson, Christer Kalén and Håkan Pleijel

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IVL
VÄSTRA GÖTALANDSREGIONEN
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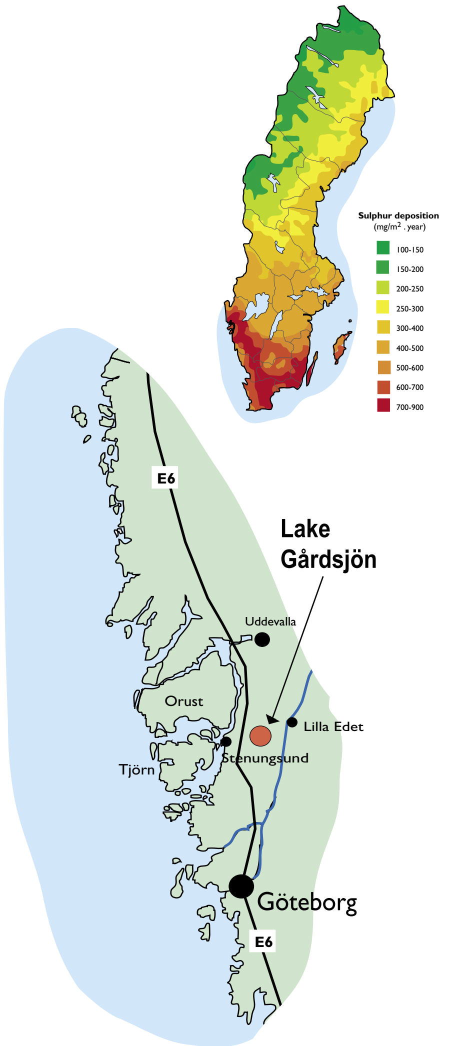
Welcome to Lake Gårdsjön



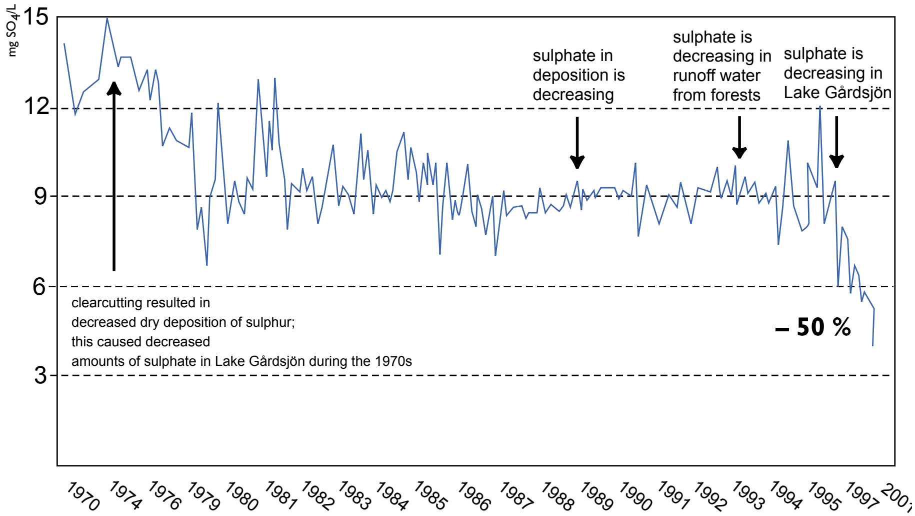
Gårdsjön is located 50 km north of Gothenburg. Drive E6 north, turn east at Stora Höga. Drive 9 km north to Ucklum. Turn right, towards Västerlanda. After 4 km turn right at roadsign Gårdsjön. Welcome!

Lake Gårdsjön, a 32 hectare clear lake, is situated in the northern part of the countryside park, popularly known as Svartedalen. The Svartedalen area stretches all the way from Lake Gårdsjön in the north to Romelanda, about 15 km to the south. Nowadays the land is covered by coniferous and mixed forest, but a hundred years ago large expanses were treeless heathland, especially in the southern part of Svartedalen. The landscape around Lake Gårdsjön and in the Svartedalen nature reserve, a couple of kilometres to the south-east, is enchantingly wild and unspoiled. It is easy to explore this area, which has several walking paths.

Research at Lake Gårdsjön

Lake Gårdsjön is also the site of unique research into air pollution and its effect on water, plants and animals. Many researchers have been or are currently involved in a variety of projects in and around the lake, which has resulted in a large number of scientific papers and several important books. Many of the results from this research have been ground-breaking and have helped explaining the relationship between acid rain and its effects on water, soils and ecosystems. The results of the research also provide very valuable background information when policy-makers at local, national or international levels make decisions on vital issues concerning acidification.

Sulphur concentrations in Lake Gårdsjön 1970 – 2000



Take a walk around Lake Gårdsjön

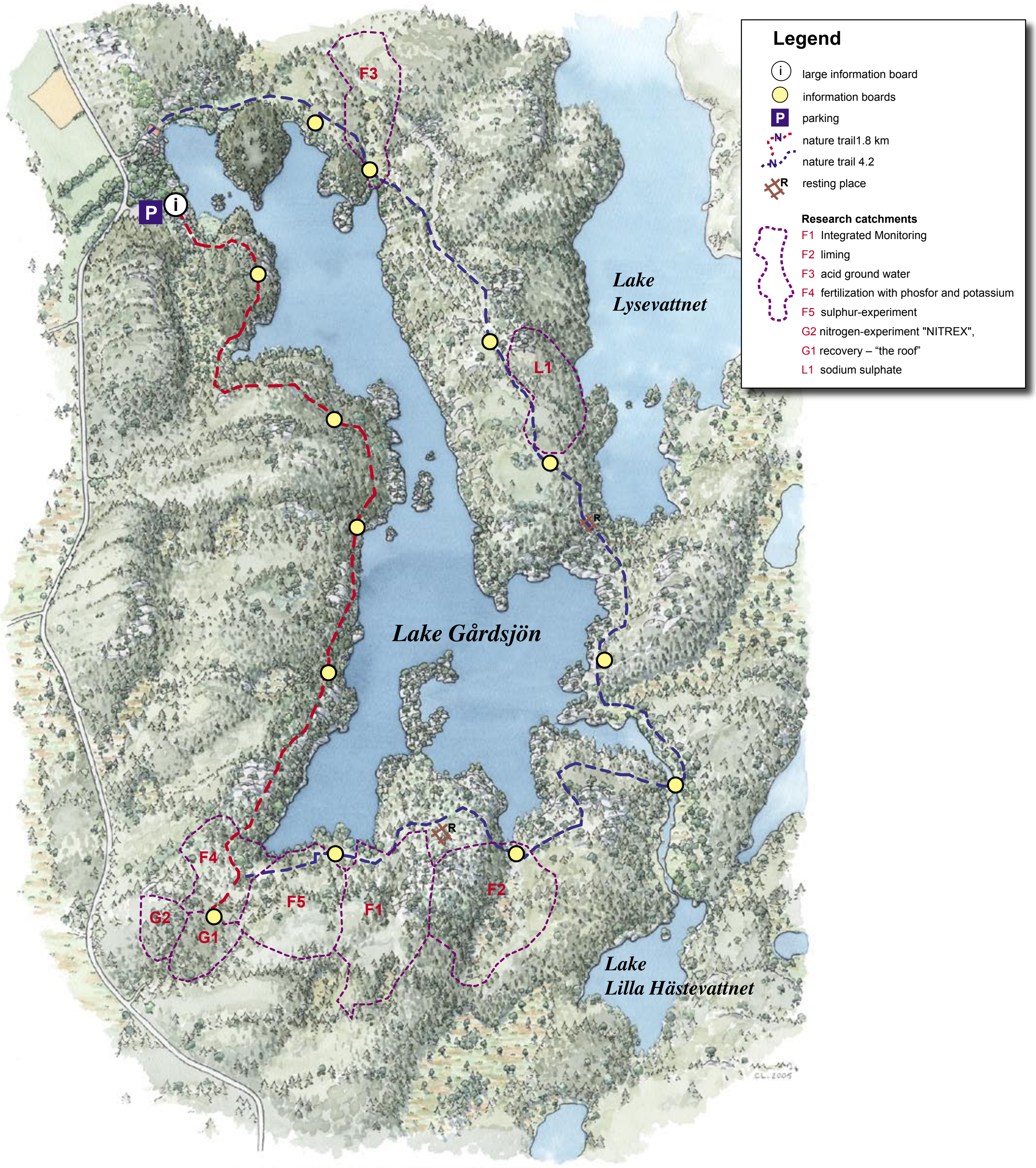
Why not explore the paths around the lake? Along the paths there are display boards that tell visitors about the local research, the plants and the animals. You have a choice of two paths, one short and one long, which take you around the Lake Gårdsjön area. A walk to the former outdoor laboratory known as "the Roof", an entire catchment area that has been roofed over, takes about an hour and a half there and back. The somewhat longer walk around the lake takes about three hours including a coffee break.

The Lake Gårdsjön nature trail (left).

The Lake Gårdsjön cabins are located at the northern part of the lake (right).

The "Roof" (down to the lef) was formely a great attraction for scientists as well as visitors.

The system of lakes is well suited for canoing.


Legend
large information board
information boards
parking
nature trail1.8 km
nature trail 4.2
resting place
Research catchments
F1 Integrated Monitoring
F2 liming
F3 acid ground water
F4 fertilization with phosfor and potassium
F5 sulphur-experiment
G2 nitrogen-experiment "NITREX",
G1 recovery – "the roof"
L1 sodium sulphate
Lake Lysevattnet
Lake Gårdsjön
Lake Lilla Hästevattnet
F3
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Rock outcrops, spruce forests and mires

Rocky outcrops are poor in nutrients but rich in species
At first glance the rock outcrops with their clumps of heather, pines and thin cover of soil seem to be rather bleak. There is no blossoming foliage or deciduous forest here. The reason for this is that the bedrock is poor in nutrients.

Take a closer look and you'll see
But there is actually a great wealth of organisms here. Get down on the ground and examine the soil and rock a little closer. What you first notice is the abundance of different cup lichens and reindeer lichens. Lichens grow very slowly. For example, a reindeer lichen grows only half a centimetre a year. Nor do lichens need much in the way of nutrients or water. They are perfectly adapted to growing in "poor" environments such as these. They also have no competition from other plants.

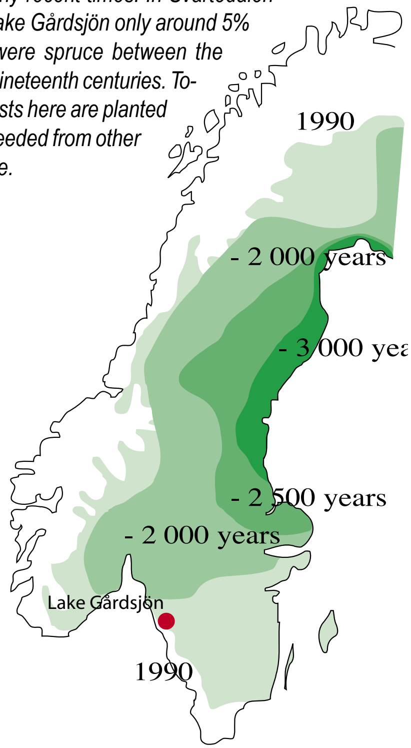
The poorest habitats of all are naturally the naked rocky outcrops. If you look a little closer you will see that they are not naked at all, but are covered by a mosaic of different lichens – crusty lichens and leafy lichens. In fact there are several hundred different lichens that live on nutrient-poor rock surfaces such as these. The lichens erode the rock and break it down.

From lichen-covered rock to forest
As soon as there is a little soil and a little moisture, mosses begin to establish. You can see green cushions of moss here and there. They consist of broom moss and niche moss. The larger, light green tufts are false bog moss. When the mosses begin to cover large areas, the soil layer is usually a little thicker and soon the first flowering plants and grasses begin to take hold. Rock campion, sheep´s-fescue and heather are early colonisers. Later on, the first pines become established, and soon forestation is a fact.

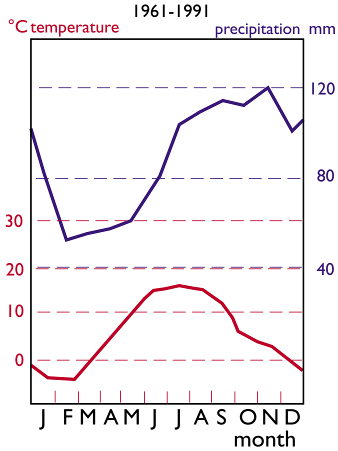
A century ago the landscape was much more open
At the beginning of the nineteenth century large parts of the Svartedalen area were occupied by treeless, grazed heathlands. Sheep and a few cattle grazed the open pastureland. Occasionally, when the heather became too widespread and woody, the land was burned. What we see today is a much overgrown version of the old open landscape. Further back in time, this area was mostly covered by deciduous forest that was dominated by oak.

The northern part of Lake Gårdsjön during winter.

The spruce is a late immigrant. It invaded Sweden from the north-east about 3,000 years ago. The native spruce came to western and southern Sweden in fairly recent times. In Svartedalen and around Lake Gårdsjön only around 5% of the trees were spruce between the fifteenth and nineteenth centuries. Today, most forests here are planted or have self-seeded from other planted spruce.



Cross-leaved heath Erica tetralix *(upper) and bog asphodel* Narthecium ossifragum *(below).*

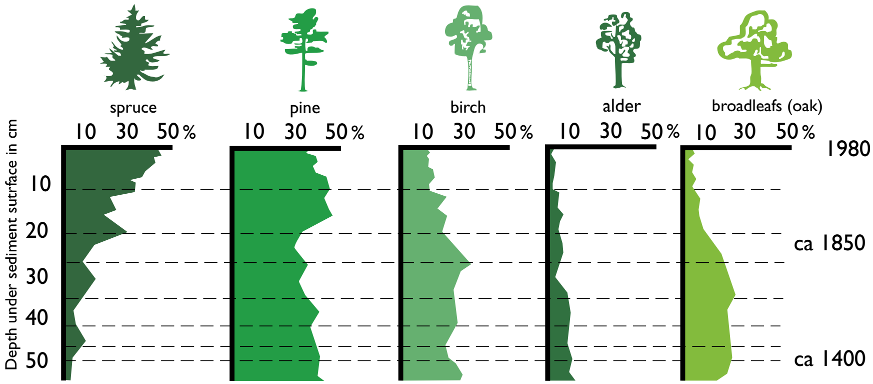


Lake Gårdsjön has an oceanic climate with high precipitation and mild winters why annual rainfall here is just over 1,100 mm. It is considerably more than at the coast, some twenty to thirty kilometers to the west. The reason it rains more here is that moist air from the sea is forced uphill and the moisture in the air then condenses and falls as precipitation. This phenomenon is known as orographic precipitation, from the Greek "oros", which means mountain. The high precipitation in the area contributes to make it one of the most acidified in Europe.

Oceanic, moisture-loving plants

The kind of plants that thrive in mild and moist coastal climates are known as oceanic. In the vicinity of Lake Gårdsjön several such plants are found, including bell-heather and bog asphodel. Bell-heather is closely related to common heather but has larger flowers. A third, but much rarer plant, is the moorland St. John's wort. As its name implies this plant grows on moorland. The presence of slender St. John's wort in Svartedalen is a relic of the time when the area was covered by open grazed moorland. Moorland St. John's wort is a threatened species in Sweden.

The lichen flora also includes several oceanic species that thrive in mild, moist areas. For example, on the smooth bark of hazel, rowan and alder in damp marshy ground you can find the barnacle lichen and the script lichen. The first looks like a little barnacle, while the latter resembles small spidery handwriting.



Pollen samples show the vegetation history of the Lake Gårdsjön area. The scientists have taken samples from different depths of the sediments of Lake Gårdsjön. Pollen from different kind of trees has been identified and the history has been reconstructed.

Mires, bogs and marshes

Mire is a collective name for bogs, fens and mixed mires. Bogs depend entirely on precipitation for their supply of water. Fens, on the other hand, also receive nutrient-rich groundwater from their surroundings. Fens are classified into poor, intermediate and rich fens, depending primarily on the availability of minerals, especially limestone. The fens around Lake Gårdsjön are all poor. Mixed mires are a mosaic of small boggy areas and small fens. The flora in the belt of fens that surrounds a bog is often more diverse than that of the bog itself. Around Lake Gårdsjön there are lots of small mires with a bog in the centre, surrounded by fens.

How is a mire formed?

On the bottom of a lake remains of plants and animals are accumulated, mixed with soil and stones. As time goes by the lake gradually fills up with sediment. When it has become sufficiently shallow, bog moss can thrive and the lake quickly fills up with plant material. Bogs are very common in humid regions with poor acid soil over cracked bedrock.

The entire bog is alive

The individual bog mosses continue to grow upwards, but die off at the base. The build-up of dead moss causes the bog to rise. The dead plant material in the bog is usually known as peat. Nutrients are in very short supply in a bog and the only water that reaches a raised bog is rain and snow. In recent years the deposition of nitrogen from the air has led to a change in the fertility of bogs. For example, pines have become an increasingly common sight.

Marshland around the stream

Along the stream towards Lake Lilla Hästevattnet there is a mixture of marsh and bog vegetation. Here you will find bog mosses (several species), reeds, cranberries, bog-rosemary and bog-myrtle. The beautiful yellow bog asphodel flowers from late summer to autumn and is only found in western Sweden. In the mires of eastern Sweden however you can see Labrador-tea, which does not grow here. A few hundred metres further south along the stream between Lake Gårdsjön and Lake Lilla Hästevattnet there is a broad border of bogland. As long as there is water running in the stream the bog cannot spread across it.

The black grouse is the undisputed king of the bogs. In early spring mornings the silence is torn by the mating calls of the black grouse cocks. This is nature's tournament and the black grouse are its knights. Whoever wins receives the favours of the hens as his prize. After courtship and mating the black grouse return to the forest, where they remain almost unseen for the rest of the year.

Dense and shady spruce forest at the southern part of Lake Gårdsjön, typical of the area. Today 50 – 80 % of the trees in the Lake Gårdsjön catchment are Norway spruce Picea abies. In the late summer and during fall, the humid wet forests are rich in mushrooms.

The lichen Lecanactis abietina *is common on the trunks of spruce trees. Creeping Lady´s-tresses Goodyera repens, prefers slightly acid soils in humid forests. Slender St. John´s wort* Hypericum pulchrum *(below), is a rare and threatened Swedish herb.*

The funnel cantherelle has dark brown fruit bodies with contrasting yellow feet and appear in the autumn. It is believed that the funnel chanterelle has become more common as a result of soil acidification.

The dead spruce trees on the west shore of Lake Gårdsjön are the result of infestation by bark beetles.

Mushrooms, acidification and liming

The delicious funnel chanterelle has dark brown fruit bodies that appear in the late autumn and are fairly difficult to spot. It is believed that the funnel chanterelle has become more common as a result of soil acidification. Some lime-loving mushrooms has become more common in certain areas around Lake Gårdsjön. This is because the soil in one of the experimental catchments (F2) has been treated with limestone powder. An important part of the research around the lake is to study and analyse changes in plant and animal life and compare these with various other influences, such as acidification or liming.

Insects

Insects are the most diverse group of organisms on our planet, with around two million known species in the world and over 30,000 in Sweden. The ones you probably will notice most around Lake Gårdsjön are dragon flies whose larvae live in the lake. You might come across a dung-beetle on one of the forest paths. Other insects whose handiwork you can see are bark beetles. The sparse and sometimes completely dead spruce trees on the west shore of Lake Gårdsjön are the result of infestation by bark beetles.

Birdlife around Lake Gårdsjön

The osprey – an occasional guest at Lake Gårdsjön.

Capercaillies at flight.

Many birds but few species

The jay is one of the most easily identified species during the summer. Beautiful and raucous, the jay has an important function to fulfil as it picks and plants acorns, which can then grow into new oak trees. In spring you can hear the calls of the black grouse from the bogs, and the capercaillie from the pine forest on high rocky ground. There are also several birds of prey here, including owls. In April you can hear the whistling of the little pygmy owl. Despite its small size it has real spirit. If you copy the call of a pygmy owl he will regard you as an unwelcome competitor and come to attack. All of a sudden you will find your hat is missing.

Capercaillie – a signal species!

The fact that there are capercaillies around Lake Gårdsjön should be seen as a sign of a healthy biodiversity. The capercaillie is only found in biologically diverse natural forest and often shares such forest with other rare species. You could say that the capercaillie is a signal species – it signals that the forest has important conservation value. The capercaillies prefers older forest with light glades and small marshes. The capercaillie's habitat must also have plenty of blueberries, which are this bird's staple diet in the summer. Capercaillies eat blueberry sprigs, leaves, shoots and berries. The capercaillie's strategy for meeting its dietary needs over winter can be summed up in three words – "pine needle feast". In order to digest this fibrous diet the capercaillies also eat grit. In old natural forest suitable dietary grit can be found under the root ball of uprooted trees, and in cultivated forest the tracks used by forestry vehicles serve as grit depots.

Division of labour between small birds

In autumn and winter you can see flocks of small birds in the forest around Lake Gårdsjön. The small bird population of these pine forests include willow-tits, crested tits, coal tits, goldcrests and tree-creepers. These birds search the crowns of the trees on the hunt for spiders and other suitable food. Ecological studies have shown that these species search for their food in different parts of the tree. Each species has its own niche. The tips of the branches are the domain of goldcrests and coal tits. The middle of the branches is the territory of the crested tits, and furthest in belongs to the willow-tits. The trunk is scoured by the tree-creeper, which climbs in a spiral from the root to the top of the tree. This remarkable division of labour between species has a practical and logical explanation. It minimises competition between the species and ensures that the supply of food is exploited as efficiently as possible.

Air pollutants and acidification

"Acidification" means that water, such as rain, streams, lakes and ground water, becomes more and more acid, and hence harmful to plants and animals. There are several causes for acidification, but the most significant of all is the emission of air pollutants – especially sulphur dioxide and nitrogen oxides. Sulphur dioxide is formed when oil and coal are burnt. Sulphur dioxide forms sulphuric acid, while oxides of nitrogen form nitric acid. Both of these acids can form compounds with ammonia in the atmosphere. This results in acid rain that falls over lands and on lakes. The acidic water attacks and dissolves metals, damages plants, kills small animals and young fish and so on.

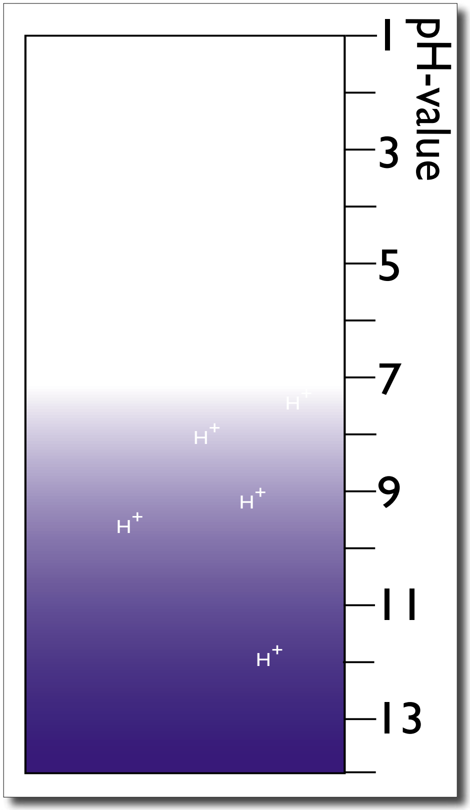
It has been estimated that around 14,000 lakes, every fifth lake in Sweden, is affected by acidification. Around 7,500 Swedish lakes are being treated with limestone (calcium and magnesium carbonate) as an effort to counteract acidification.

Base cations (calcium, magnesium and potassium) in the soil and water naturally counter acidification. However the continuing deposition of acidifying substances consumes all the buffer agents and decreases the base cation content of the soil, resulting in increasing acidity and reduced pH of the soil.

Nitrogen compounds from traffic, ammonia from farmlands and...

sulphur dioxide from burning of coal and oil...

...form acid rain that acidifies soils and water.



The pH-scale

The lower the pH value the more acid is a water solution (the more hydrogen ions it contains). The pH scale is logarithmic, which means that each unit on the scale represents a factor of 10. At a pH of 5 there are ten times more hydrogen ions as there are at a pH of 6. If the pH value of a lake drops from the neutral pH of 7 to a pH value of 4 it means that the water has become 10 x 10 x 10 = 1000 times more acid! When pH falls below 5.5 the young fish die and the reproductive ability of fish such as salmon, sea trout, minnows and roach deteriorates. At pH 4.5 pike and perch gradually disappear, and below pH 4.0 the lake appears more or less dead. Individual species of insects, such as pond skaters, can however thrive in such conditions.

The lake – a mirror of its catchment

In soils and water there are processes that counteract acidification. Substances retarding the pH decline (see figure) are named buffers. In a lake, the buffer capacity is mainly determined by the availability of bicarbonate ions. These are delivered by the weathering of minerals in the soils of the drainage area of the lake. Thick layers of fine-grained, easily weathered minerals, such as lime, provide the lake with an abundance of bicarbonate. Such a lake is insensitive to acidification. In the Svartedalen area the soils are thin, relatively coarse and poor in minerals with a high weathering rate. Therefore, the lakes here are sensitive to acidification. In sensitive soils, the weathering is not keeping up with the elevated addition of hydrogen ions. As a consequence pH drops. On its way though the soil profile, down to the ground water, and further to the lake, the acid water brings with it base cations (calcium, magnesium and potassium). Thus, the soil becomes poor in nutrients. Under strong acidification aluminium dissolves in the soil water. Aluminium is toxic to fish and most likely also harmful to plants. When aluminium starts to become dissolved, pH does not drop much further, but the ecosystem is now severely damaged by acidification.

Springtime – critical for the environment

The most sensitive time for the environment is spring. This is when nature reawakens and needs plenty of fresh water, nutrients, sunshine and warmth. Unfortunately, the winter snow and the frozen soil have accumulated an abundance of acidifying substances, which are released when the winter snow melts and the spring rain washes the soils. It is today common wisdom that the spring thaw acts like an acid shock on waterways.

The only way out!

In reality, there is only one way out of the acidification tragedy. The solution is to dramatically reduce or completely eliminate the use of fossil fuels, such as coal and oil. If we did this we would also solve a whole host of other, equally serious, environmental problems simultaneously. For example, this would reduce ground-level ozone and reduce the release of the greenhouse gas carbon dioxide into the atmosphere.

Critical load

If acid precipitation was brought below the critical load, our waterways and the plants and animals living there, might recover to their original state of health. One of the most important tasks of the research around Lake Gårdsjön is to find out if and how this can be made.

Acidification of lakes

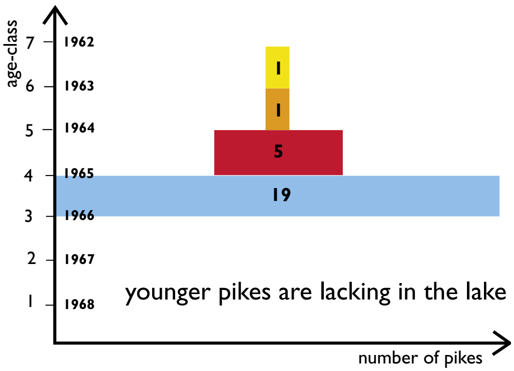
During the 1960s and 1970s the first observations of disappearing fish populations were made in soutwestern Sweden. Sensitive fish species like roach, arctic char and minnow were lost and salmon and sea trout decreased.The decline in fish stocks were closely linked to low pH in the water. The low pH was caused by atmospheric depositon of acidifying sulphur and nitrogen. Already in 1969/70 water and fish was sampeled in Lake Gårdsjön. The fish stock was very sparse – only 1.5 perch per hectare (ha) and a total of three northern pike was found in the 32 ha large lake which compare to thousands of fish in a normal forest lake.

Start of the Lake Gårdsjön project

The Gårdsjön project started in 1978 with scientists from all of Sweden and with the aim to study the processes of acidification in detail. Today, the research aims to study the whole forest ecosystem including air, soils, ground vegetation, trees, groundwater and surface water. In Lake Gårdsjön and the upstream Lake Stora Hästevatten, monitoring of water chemistry started 35 years ago and is still ongoing. Monitoring in runoff from the forested catchment started in 1978 and represents one of the longest data sets on chemistry from an acidified forest catchments.

Fish populations in acidified lakes

In Lake Gårdsjön acidification has caused the fish populations of perch, roach, northern pike and european eel to disappear. Perch, which is a common fish species in Swedish fresh waters, can tolerate quite acid conditions, but disapperar when pH is lower than 4.5 - 4.7. Roach is more sensitive and reproduction when pH is lower than 5.5. Under natural water chemistry, eggs of perch are transparent, but in acid water they become opaque due to coagulation of the proteins in the egg. The fish embyo dies insde the egg. In many lakes the first vertebra of the backbone in perch are damaged and the fish develops a humpback. The damage to the backbone appears when the perch fry is hatching and tries to break the egg wall. In the Anråse å watershed, which has more than 50 lakes and where Lake Gårdsjön is situated, roach died out during 1960s and the last roach population disappeared in 1972 from Lake Ålevatten.



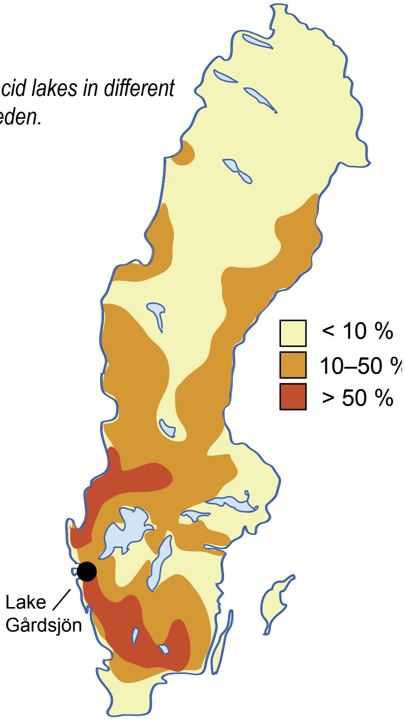
The number of northern pike in each year class as well as the year of hatching in Lake Mörtevatten during the autumn 1969.

Lakes	Date	pH	SO_4^{2-} mg/l
Mörtevatten	1969-10-02	4.6	-
	1969-10-25	4.6	8.48
Kroksjön	1969-10-02	4.8	-
	1969-10-02	4.8	10.5
St. Äggdalsjön	1962-11-21	5.8	-
	1969-11-26	5.8	13.6
St. Nöjevatten	1962-11-21	5.9	-
	1969-11-26	4.8	10.3
Timmervatten	1962-11-21	5.9	-
	1969-11-26	4.6	11.2
Mörtevatten	1962-11-21	5.9	-
	1969-11-26	4.6	12.7
St. Örevatten	1960 March	5.0	-
	1965-03-25	4.5	-
Härsevatten	1969-11-26	4.5	9.7

Water analyses of pH and sulphate show that the lakes in the Anråse å watershed were acidified during the 1960s.

A fish fry is very sensitive to acid water.

Percetage acid lakes in different parts of Sweden.



Fish decline in the Anråse river

During the 1950s streams in the Anråse river watershed had strong fish populations of minnow, brown trout and sea trout. Minnows are very sensitive to acid water and disappeared from most of the area during the 1960s. The sea trout, which had one of the largest populations in southwestern Sweden, was reduced by some 80 to 90% during the 1970s. Acid shocks during autumn rains and high flows during snow melt in spring were the main causes of the decline. Acid shocks were also the main cause to the total whipe out of the fresh water pearl mussel from the stream bottoms in the early 1970s.

Inorganic aluminium - the main fish killer

Today we have learnt that it is not only the acidity of the water and acid surges that kill the fish. When the shallow soils in forested areas become acidified to a pH below 5.0 inorganic aluminium is leached out of the soil profile and is transported to lakes and rivers. The inorganic aluminium is precipitated on the gill surface of fish and prevents uptake of oxygen by the fish, though there is a lot of oxygen in the water. The fish die from suffocation. This toxic form of aluminium is leached out from the forest soils although the acid sulphur deposition has decreased substantially during the last 15 years. Particularly during high flow of water during spring and in autumn after dry summers shockwaves of acid sulphur are leached out from wetlands. This is caused by oxidation of reduced sulphur in soils where the groundwater table has been lowered. At these sulphur shocks toxic aluminium is leached out into the water. Also storms causing increased deposition of salt from the sea and high concentrations of nitrate may cause leaching of toxic inorganic aluminium.

Salmon and sea trout from the Anråse river. The two uppermost fishes (salmon and sea trout) lived two years in the river and migrated to the sea in the next spring. The two small fish are one summer old. The picture was taken during early autumn.

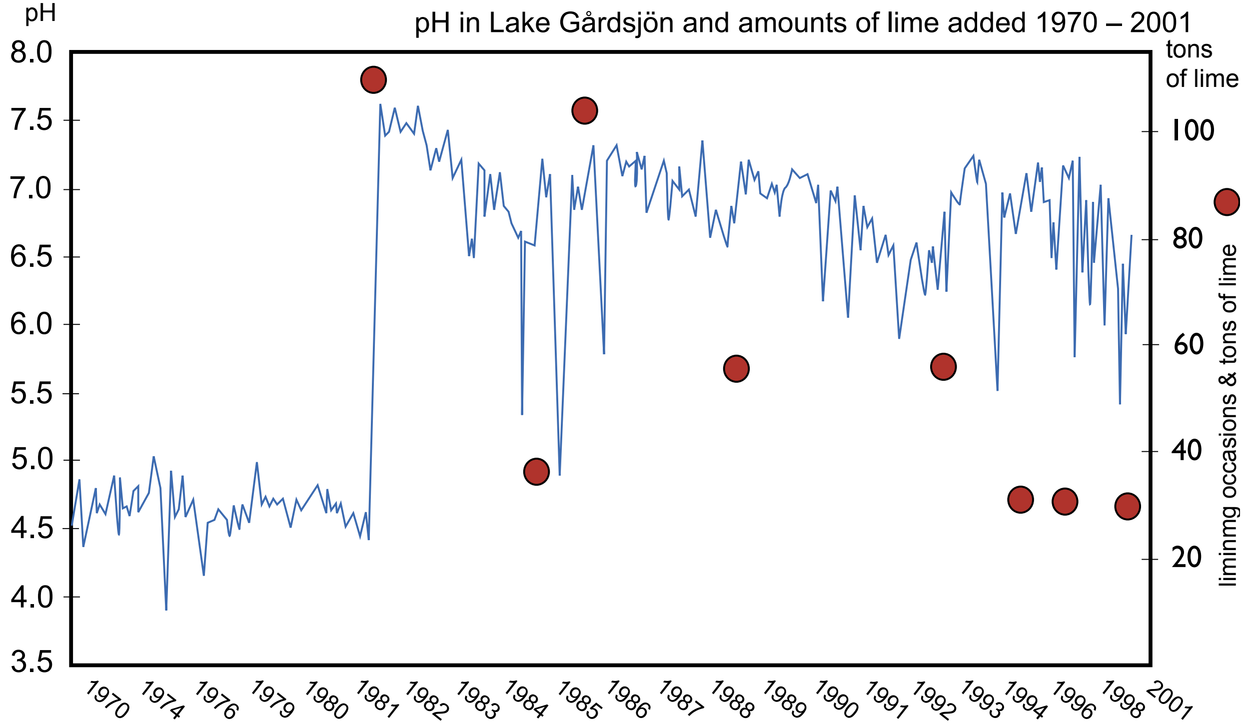
Lake liming result in recovery of fish stocks

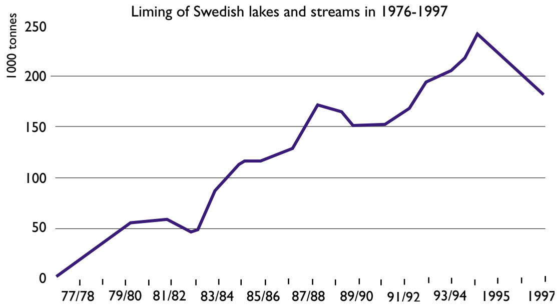
After the start of lake limning in the Anråse river watershed the sea trout population has increased by more than 50% and perch and northern pike population in the lakes have increased. Roach was reintroduced and has spread to many lakes through the watershed. The arctic char in Lake Stora Holmevatten in a nearby watershed died out during the 1950s but was sucessfully reintroduced after liming of the lake. The arctic char population is now sucessfully reproducing in the lake again. Liming of lakes and rivers in southern Sweden may have to continue for many years into the future. Primarily to avoid fish kills caused by toxic inorganic aluminium, which continues to leach into lakes and streams from the acidified forest soils though the atmospheric deposition has decreased by some 70 - 80% since the biginning of the 1990s.

Rainbow trout has been introduced in many limed lakes.

Lake Gårdsjön first limed in 1982

Since 1982 Lake Gårdsjön has been treated with limestone ($CaCO_3$) regularly, and the effects have been studied in detail. The liming of lakes and wetlands leads to a very rapid rise in pH and a reduction in aluminium. This means that plants, small animals and fish can recover quickly. However, liming must be repeated regularly at intervals of a few years to ensure that the positive effects are maintained.





Liming of Swedish lakes since late 1970s. The largest amount used in a single year was 250 000 tonnes of limestone powder.

Reduced sulphur deposition allows acidified lakes to recover

During the 1990s the deposition of sulphur fell by 70 % and the sulphur concentration in Lake Gårdsjön has decreased by more than 50 % (above) and damage from acidification has been reduced.

In the Lake Stora Hästevatten, which is upstream of Lake Gårdsjön, researchers have been monitoring the acidified ecosystem of the lake for many years by studying the water chemistry and diversity of species of plants, plankton and bottom-living animals. There has been a rise in pH in recent years, but this change is very gradual. There are still mats of moss on the lake bottom and the acid-tolerant species of plankton and invertebrates are still dominant, but after over 20 years of absence the acid-sensitive fresh water louse *Asellus* has returned to the lake.

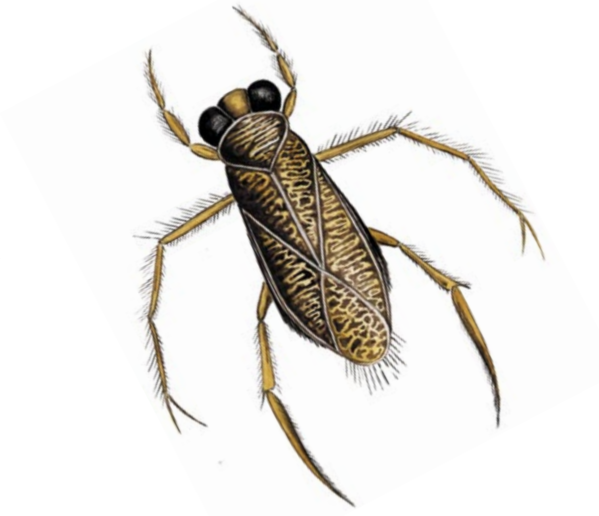
The reason for the slow recovery of the Gårdsjö area is the severe depletion of base cations (calcium, magnesium and potassium) and a soil profile that is now dominated by hydrogen ions (H^+) and aluminium. The soil's "acidification memory" is still strong, which means that it will take substantial time for the lake to recover from the damage caused by acidification.

Liming of running water.

Liming in Lake Gårdsjön. The flooter carries 10 tonnes of limestone powder.

Abiotic and biotic factors

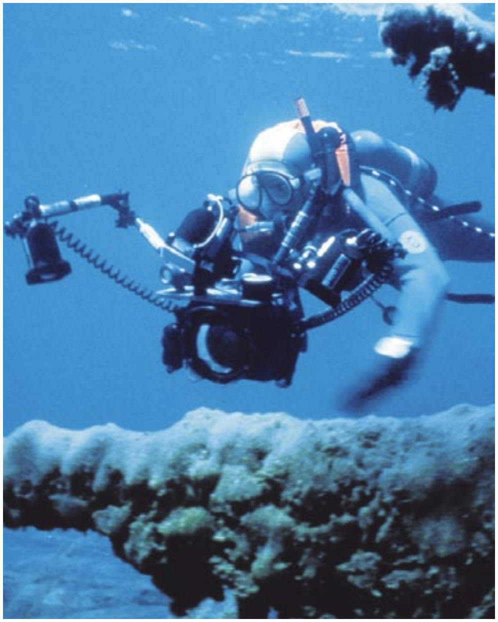
pH, inorganic aluminium, calcium and carbon dioxide are exampels of abiotic factors important for biological effects in acidified lakes. When a lake is acidified, low pH and /or increased concentrations of inorganic Al may result in the diappearance of seveal fish species. Acid water has high concentrations of carbon dixide which result in growth of mosses like *Sphagnum* on the lake bottom. Liming of an acid lake results in decreased concentrations of carbon dioxide and decreased growth of *Sphagnum* as well as decreased levels of inorganic Al, higher pH and calcium, which allow sensitive species to survive. Sometimes these species can increase from a few individuals, or by migration upstream, fly to the lake like mayflies or be introduced by man.
Biotic factors are those directly caused by another organism. The loss of fish species from lakes results in large biological effects in acidified lakes. After liming of acid lakes fish populations increase again. This results in large biological changes due to increased predation and competition between species.



An acid tolerant species. When fish disappear from lakes, water boatsmen Glaenocorisa propinqua *sometimes appear in large numbers.*

Would you like to learn more about dragonfly larvae?

If you come to a lake and look along the shoreline for wildlife you may find a sort of yellow-greenish-brown dragonfly larva that has three lengthway stripes on its belly. You have found a marsh dragonfly. If so, you can immediately say that there are few, if any, fish in the lake! The habits of the marsh dragonfly larva mean that it cannot share a lake with fish. March dragonfly larvae are active twenty-four hours a day and move long distances, even in daylight. As a result they are very easy prey for fish and can only be found in environments that are more or less free of fish. Other species of dragonfly, which can live together with fish, have larvae that hide in the bottom silt during the daytime, when the fish are active. They only search for food at night under the cover of darkness and then only move short distances. So if you are hoping for a good day's fishing you should avoid lakes that have lots of marsh dragonfly!



A severly acidified lake with crystal clear water.

Acid lake

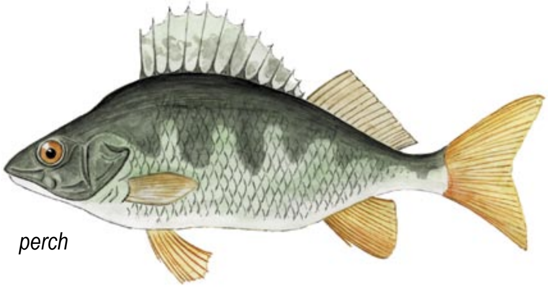
In acid water with low pH (4-5.5) fish eggs and larvae dies. Few older fish can survive.

Most mayfly species disappear in acid water. Crayfish species, molluscs and mussels have problems formig shells and die out.

Dragonfly larvae, diving beetles and chaoborus larvae are easy pray for fish. These species increase when the fish disappears. Some of these species only appear in lakes which are empty of fish.

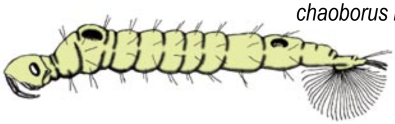
Bog mosses *Sphagnum* sp. increase due to high concentrations of carbon dioxide in the acid water. Acid lake water becomes clear due to reduced concentrations of organic carbon and plankton populations. In a clear lake sunlight reachs deeper into the lake water.

The goldeneye increases in acid lakes. Like the fish it prefers large insect larvae for food. The fish eating blackthroated diver, on the other hand, disappears from the acid lakes.

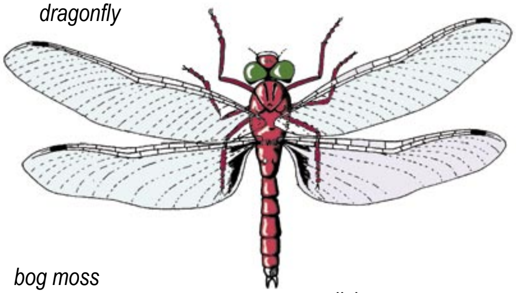


perch

chaoborus larvae



dragonfly



bog moss

diving beetle

goldeneye

blackthroated diver

Limed lake

Higher pH (6-7) results in normal reproduction of the fish species and the fish populations can recover.

All mayfly larvae do well in water with a normal pH. Crayfish, molluscs and mussels have no problem building shells.

Only few individuals of dragonfly larvae, diving beetles and other large insect larvae survive the fish predation.

The bog mosses disappear from the limed lakes due to lack of carbon dioxide.

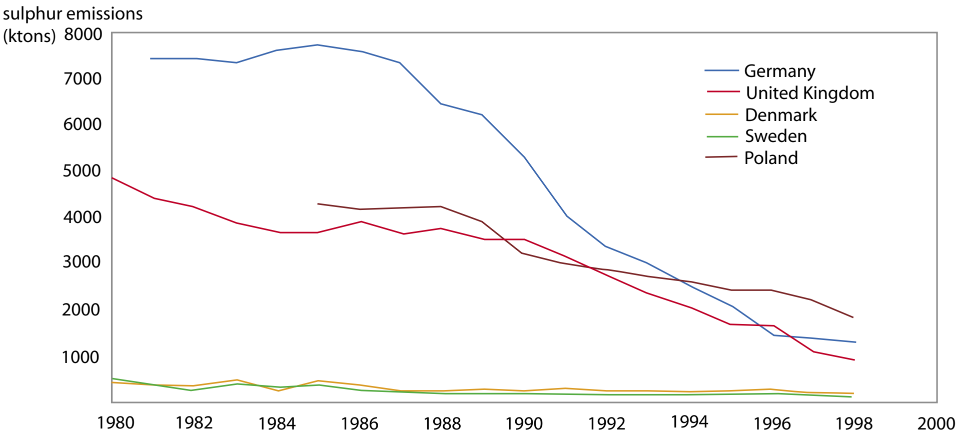
Some aquatic plants, such as pondweed and water weed use bicarbonate for their photosynthesis, and often return after liming. The alga *Nitella*, which is brought in by Canada geese, reestablishes itself on the bottom of limed lakes.

The goldeneye numbers are reduced while the blackthroated diver returns to the lake.

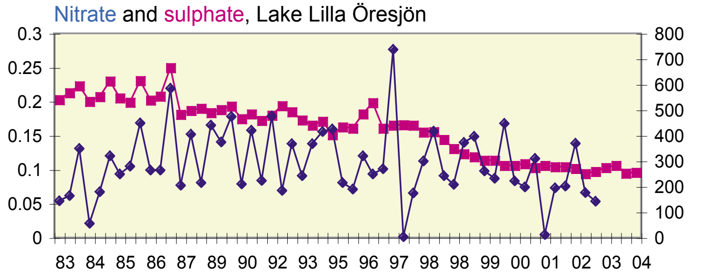
You can still hear people talk negatively about the development of the environment – and certainly, there are many problems to worry about. But if you look back two or three decades, you'll find that many environmetntal issues have improved! Big problems like local eutrophication of lakes and running waters, metal pollution, and acidification of inland waters are among them.

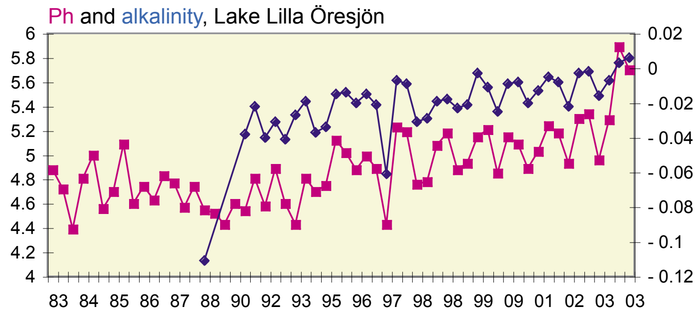
Some of us can remember lakes and rivers before we had sewage plants in the municipalities and environmental legislation first appeared in 1969; dead fish in the lakes and rivers, extreme algal blooms and fish that had too high mercury content. Very little of this can be seen today – at least in our county, Västra Götaland.

Not as obvious is the ongoing change in water quality in our lakes as a consequence of declining deposition of airborne acidifying substances. Just east of Stenungsund on the Swedish west coast, are forest areas that have received lot of acid deposition from Swedish as well as foreign sources. As mentioned earlier, the soil is very thin and the rock has little buffering capacity against acidifying substances. The result is that lakes and rivers since long ago are so acidified that fish can't survive without liming. In many cases, liming has been the only available method to allow a fish fauna to persist and make angling possible.



Sulphur emissions (ktons) from many sources have decreased substantially since the early 1990´s.





But the situation has changed in the nineties, the emission reduction of especially sulphur has been extensive in England, Germany and Poland, i.e. those countries that have contributed most to the deposition on the Swedish west coast. This, together with large efforts from regional industries, has caused the sulphur deposition on the west coast to diminish with as much as 60 to 70 percent at monitoring stations close to the coast!

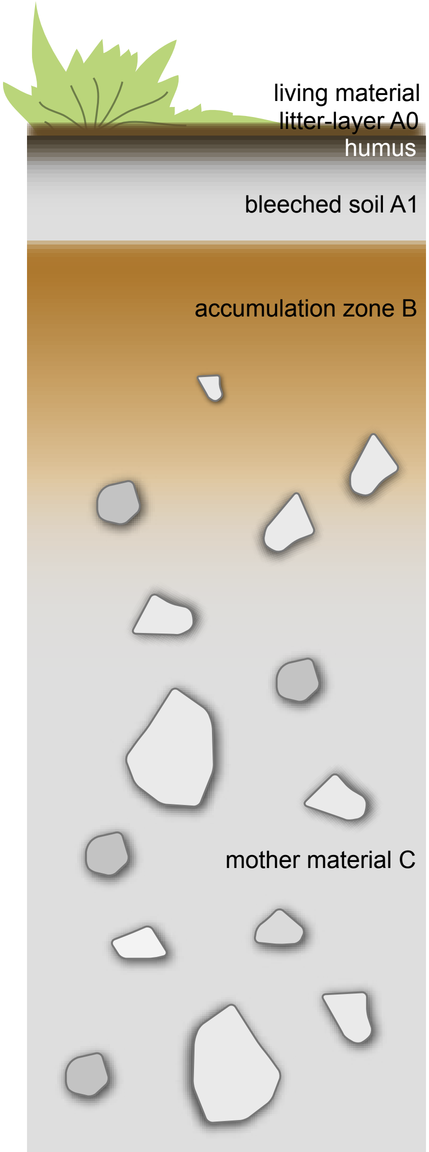
In the county Västra Götaland we have 15 reference lakes for studying acidification. This means that you are not allowed to lime or do anything else that can have an impact on the water quality. Many of these lakes were heavily acidified when the monitoring started in middle of the 1980s. One of these lakes – Lilla Öresjön, on the southern border of Västra Götaland, has during 2003 passed the important limit between acid and not acid, the so called zero alkalinity, without any other measures than reduced deposition of acidifying substances! The sulphur content in the lake has decreased, the pH value has increased as well as the alkalinity. In the figure you can see the pH value make a leap just as the zero alcalinity limit is passed. If the situation will last (one must probably count with one or two drawbacks) it will be possible for fish and other organisms to establish once again. The development is similar in a lake called Härsvatten which is situated close to Gårdsjön. If the ongoing improvement continues in Härsvatten, this lake will pass zero alcalinity within the next ten years. Many other acidified lakes in the area will probably follow!

As the situation in the acidified lakes improves you can ask if we can stop liming other acidified lakes. The answer is unfortunately no! Even if many of the reference lakes show the same positive pattern and this probably also is the case with limed lakes, the liming must go on for many years to come. Most lakes start from a worse position than Lilla Öresjön and Härsvatten and unfortunately it can take decades before most of the lakes can manage without liming. But most importantly, it's getting better, even if it moves slowly.

Brown trout female squezed on eggs in Gårdsjön (to the left). Lake Gårdsjöns own trout hatchery (above) and six months old youngsters of trout, ready for freedom (below, right).

Arctic char, formerly present in many lakes i southwestern Sweden, has been successfully reintroduced in Lake Gårdsjön (left).

Soil acidification



Soil characteristics

The geology around Lake Gårdsjön consists of granite and gneiss that are around 1.7 billion years old. The last ice age polished the rock and left shallow moraines in the hollows in the terrain. After many thousands of years, large expanses of the surface still consist of bare rock covered by lichen or a thin layer of soil. The average depth of the soil in the catchment areas that surround Lake Gårdsjön is just 0.5–1.0 metres and it consists of a podzol or peat soil mixed with sand or fine sand. The moraines in the area were formed from local, slowly-weathering rock, which has left the soil poor in base cations (calcium, magnesium and potassium) and other nutrients.

Natural acidification

Since the mid-nineteenth century Norway spruce has become increasingly widespread, at the expense of oak, birch, alder and pine, which previously dominated the forests. The predominance of spruce over the last century has led to increasing acidification of the top layer of soil. This acidification is caused by the humic acids that are leached out of the conifer litter (fallen needles, cones and twigs). These humic acids remain in the top layer of the soil and therefore do not usually contribute to the acidification of lakes and waterways that have clean, clear water.

Airborne acidification

Sulphur is deposited on forest land as a result of precipitation and dry fallout (sulphur dioxide gas and sulphate particles). A large proportion of these deposits are trapped and accumulate in the crowns of the trees and as a result sulphur deposition in an old spruce forest can be more than twice that of young forest with an open canopy. Sulphate ions (sulphuric acid) can, in contrast to humic acids, be transported right through the soil. Around Lake Gårdsjön this sulphur deposition has been taking place for over a hundred years, but the greatest deposition has occurred over the last 40–50 years. When sulphuric acid is transported though the soil the hydrogen ions (H^+) in the percolating water are replaced with calcium, magnesium and potassium. Once the soil has been acidified, aluminium, manganese and heavy metals, such as cadmium and zinc, are also leached out into the groundwater and into the lake.

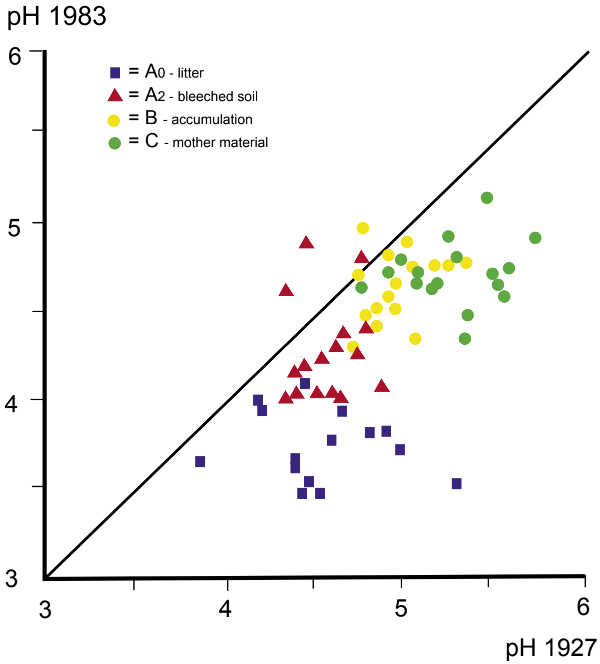
Acidified soil needs long time to recover

Large areas (60%) of southern Sweden, that have slowly-weathering rock and thin soil cover, have been depleted of base cations, acidified, and are now dominated by toxic inorganic aluminium that is leaching out into the waterways. Aluminium, in turn, can bind phosphorus in the soil. This means that strongly acidified forest land is acting as a filter for phosphorus. Because phosphorus is a scarce nutrient in poor forest lakes, these lakes are becoming increasingly infertile. Consequently, even in the long-term the lakes will not support the same stocks of fish and other organisms as they did 50–100 years ago.

The soil remembers acidification

Some of the sulphur has been bound up in the soil and will leach out as sulphur deposition from the atmosphere decreases. Calculations show that the soil's sulphur "memory" will take more than 20 years to fade away. The soil's memory of its loss of calcium, magnesium and potassium – its "base cation memory" means that it will take the lakes a long time to recover from acidification, perhaps 100 years before the pH returns to the level it had before acidification.

In central and northern Sweden, where forest lands have not been severely acidified by sulphur deposition, the soil has not yet developed a "sulphur memory" or "base cation memory". This means that in these areas recovery will take much less time as sulphur deposition decreases.



Forest professor C. O. Tamm found his fathers measurements of soil acidity from Tönnersjöheden in the county of Halland. The measurements from 1927 were repeated with the same method in 1983. The pH was found to have decreased by one unit in the whole soil profile (left).

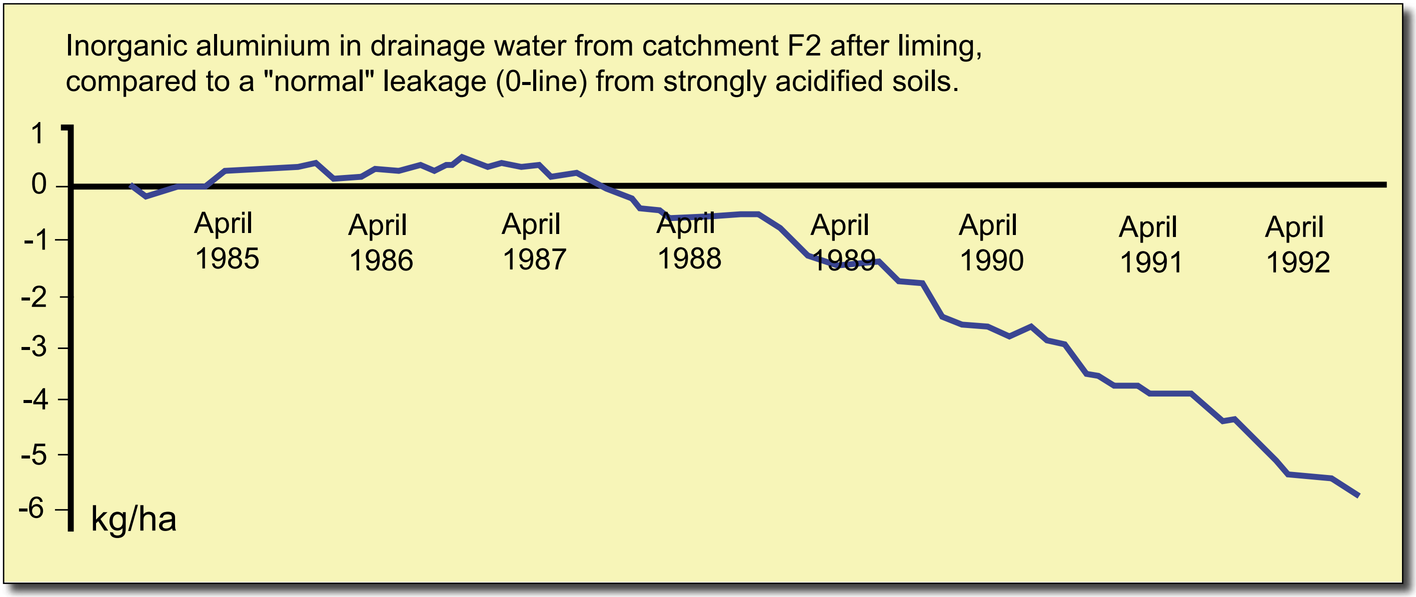
Liming of forest soils

Liming on ground in the F2 area at Lake Gårdsjön.

Liming - a solution for acid soils?
The acidification of forest land is a big environmental problem – the trees suffer and toxic aluminium leaches out into lakes and waterways. Trials have therefore been performed to find out whether treating forest land with lime is an effective measure against acid run-off water and to protect against further acidification of the soil.

An entire catchment area limed by hand
The entire F2 catchment area was limed by hand with 1.5 tonnes of finely ground dolomite per hectare by researchers in May 1984. In 1986 half the area was limed with a further 4.5 tonnes per hectare. The trials at Lake Gårdsjön are especially important since there is an identical comparison area, F1 (now a national and international monitoring area for air pollution).

Results of liming
The pH of the soil has increased and calcium has been fixed in the upper layers of the soil. During the first ten years after treating with lime only around 3 kg of calcium per hectare, or about 1% of the added amount, was transported away in the run-off water. The remaining 99% of calcium stayed in the soil.



Of the smaller amount of magnesium that was present in the dolomite around 30 kg per hectare (about 10%) was leached out in the ten year period following the first liming treatment. Magnesium is obviously more mobile in the soil than calcium, which is bound more tightly to organic material.

The strong binding of calcium in the upper layer of the soil led to increased leaching of acidic ions, such as hydrogen ions (H^+) and aluminium, into the run-off water. The acidic ions leaked out during the first two years due to the low dosage of lime.

It takes 50 years for lime to penetrate half a metre into the soil

The slow passage of calcium down through the soil (about 1 cm per year) means that it will take a very long time before the entire soil profile, including deep soil water, groundwater and run-off water are "fully limed". Fears have been expressed that the liming of soil would increase the mineralisation of nitrogen and sulphur in the soil organic matter. This would in turn lead to the leaching of nitrates and sulphates into the water.

For around 10 years after the land was treated with lime, sulphur leakage increased insignificantly above the supply rate from the atmosphere, or by a total of 3 kg. This is equivalent to 1% of the deposition from the atmosphere over the same period.

Puffballs

RESULTS FROM F2

- Nitrogen levels, in the form of nitrate and ammonium, have not increased in run-off water following liming.
- The pH of run-off water from the limed forest land has not changed and remains very low.
- Levels of toxic inorganic aluminium and manganese have fallen by around 50–60% over a ten-year period.
- Lichens on the ground and tree trunks that came into contact with lime have died.
- Mushrooms like fly agaric and puff-balls, which are found in lime-rich areas of Sweden, are now appearing in large numbers in the limed F2 area, but nowhere else in the surrounding forests.

Recycling of wood ash

A stabilised ash product dissolves slowly and is therefore of no threat to the ecosystem.

Spreading of ash is one way to accomplish a quick recovery of waters.

RecAsh is an EU financed project with the objective to promote recycling of wood ash through improvement of the knowledge among those involved in the activities.

www.recash.info

Intensive use of forests causes soil acidification

The use of biofuel has increased dramatically in Sweden. One type of biofuel is harvest residues that remain when a forest stand is felled. As tree biomass is renewable energy, these residues are a good alternative to fossil fuel. However, a consequence is also that the removal of nutrients from forest soils is greatly increased. This removal is greater than what can be compensated for through weathering and other natural processes. Forestry therefore contributes to acidification and to a more uncertain future regarding availability of important nutrients.

Acidification caused by forestry

As the deposition of acid substances is decreasing and the removal of nutrients from forest soil is increasing through whole tree harvesting, we experience a rapid change in the relative importance of different causes for soil acidification. The contribution to soil acidification caused by forestry is increasing and in some parts of Sweden it is estimated to be of higher magnitude than the deposition. The contribution is, however, not comparable to the peak years of acid rain during the 1970s and 1980s. The National Board of Forestry has estimated that weathering and nutrient deposition is enough to compensate only the removal of nutrients from conventional harvest of stemwood. However, these compensating processes are not enough if harvest residues also are extracted during felling of the stand. The National Board of Forestry therefore recommends that wood ash is recirculated to the forest soil in stands where whole tree harvesting is conducted.

Spreading of ash is predominantly made on ground in thinned stands.

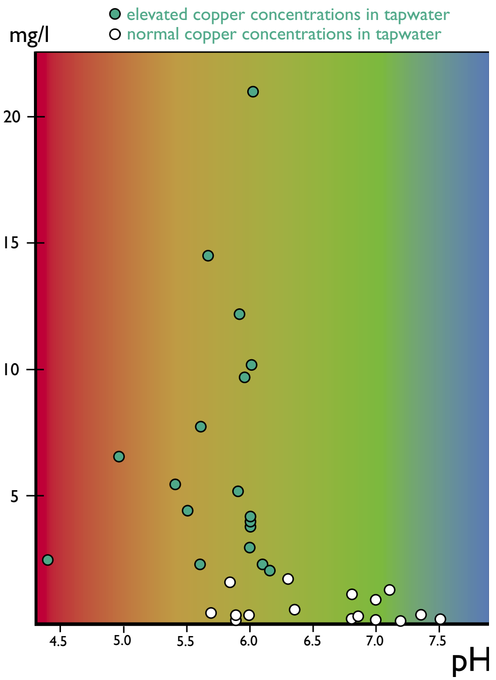
Nutrient recycling

After harvest residiues has been incinerated much of the nutrients that once was extracted from the soil is found in the remaining ash. By recirculating the ash, nutrient losses are thereby compensated for and acidification due to whole tree harvesting is prevented. Recirculation of nutrients counteract an increased leaching of acid and aluminium rich water to streams and lakes. Instead, it is likely that the water quality in South-West Sweden will improve so that fish and other freshwater organisms will have a healthier environment.

Lime and wood ash – speeding up the recovery

Since the natural recovery of strongly acidified forest soils is very slow, a restoration program is today under preparation to speed up the recovery. The current strategy within the National Forestry Board is to treat to forested land within whole catchment basins (>150 ha). Both limestone and wood ash is used in this treatment, where the liming is financed by the government and ash by the energy production industry. The objective of the treatment is to accomplish a lasting restoration of soils and water to a condition that allows organisms to once again flourish in these environments.

Groundwater



Concentrations of copper in tapwater from households where water has been standing in copper pipes overnight.

The first alarm signals

Following the dry summers of 1975 and 1976 high concentrations of hydroxides of aluminium, manganese and iron were discovered along a 2 km long stretch of the River Stenunge å in Stenungsund municipality. Native stocks of sea trout were severely depleted and had disappeared along several stretches. Investigations showed the reason to be severe acidification, with pH values below 3.5 in the groundwater that supplied the river. The low pH values were caused by very high levels of sulphuric acid. Drought had lowered the groundwater, allowing sulphide in the soil to oxidise into sulphuric acid.

Groundwater strongly acidified

The shallow groundwater around the lakes Gårdsjön, Lysevatten and Bredvatten also revealed low pH values in 1977 and higher levels of toxic inorganic aluminium than in the acidified lakes. It was thought that the forest soil had been affected by equally severe acidification as the lakes and waterways by the deposition of sulphur from the air.

Widespread acidification of well water

A survey of the acidity of shallow and drilled wells that was carried out in southern Sweden showed that around 75% of the excavated shallow wells had a pH lower than 6.0 in parts of Västra Götaland and Halland counties. The drilled wells generally had a higher pH, but in the counties examined 10–35% of these wells also had a pH lower than 6.0.

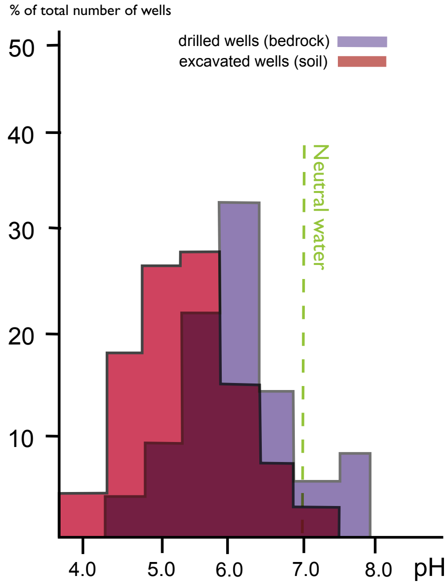
Corroding water pipes

Copper pipes and other metal objects that come into contact with the acidic water suffer corrosion, and metals are leached out. The problem of copper in tap water can be temporarily solved by flushing out the pipes. Other solutions are to add lime to the wells, or install lime filters.

The acidification of groundwater is widespread in Sweden and there will be considerable problems for many years to come. The use of stainless steel pipes instead of copper and iron may solve some of the problems. The elevated levels of metals (aluminium and manganese) that are leached out of the soil remain a problem however.

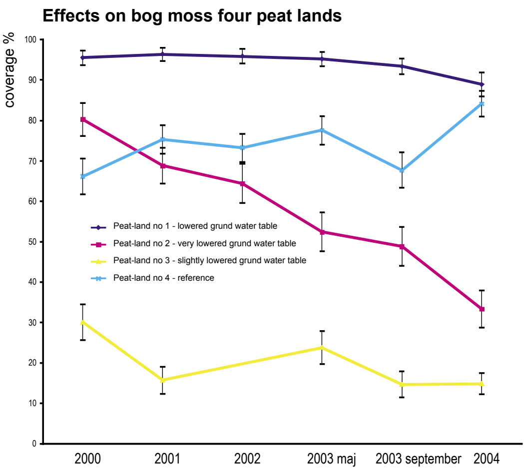
Research into decreased groundwater levels at Lake Gårdsjön

A research project on effects on groundwater formation and chemistry by a decreased groundwater level was started in December 2000 with a pumping of groundwater at a depth of 50 m below ground in a borehole in the crystalline bedrock. The catchment was divided into three parts separated by hydrologic dams equipped with continuous measurements of water flow. The pumping was performed in the middle section of the three parts. During the summer 2001, May until October, the groundwater level decreased by more than five meters. This resulted in a total drying out of the wetland in the middle section as well as in the upper part of the bedrock underlying the peat in the wetland. Such a drying out of the wetland has probably not occurred over a period of several hundred, maybe a thousand, years in the catchment. During the dry months of late summer air penetrated the 'wetland' peat soil. In the autumn 2001, high precipitation amounts again increased the groundwater level in the bedrock and in the wetland, which resulted in runoff water with very high concentrations of sulphate which resulted from oxidation of reduced sulphids (oxygen came in contact with the deep soil). The drought also resulted in severe effects on the flora of the wetland with some species disappearing and some species increasing.



pH is lower in excavated wells compared to drilled wells.

Demonstration of vegetation monitoring at the grundwater research site.

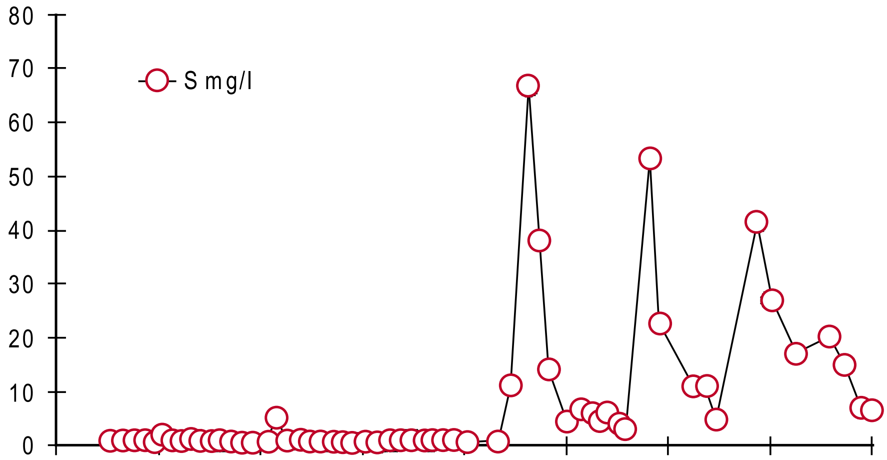


The vascular plants and the moss vegetation has also been affected by the lowered ground water. In the most "lowered" peatland bog mosses Sphagnum *spp. was dying.*

Results from the grundwater project

Atmospheric deposition of sulphur in Sweden has decreased by some 80 % during the last 15 years. This has resulted in generally decreased sulphate concentrations in groundwater and surface waters. This project, however, shows that artificial hydrological alteration in an acid wetland can reverse this trend and result in increased acidity and sulphate concentrations. The experiment included monitoring of two catchments in relatively virgin conditions. An experiment was initiated in one of the catchments through intensive groundwater extraction. The extraction caused the runoff from the experimental catchment to decrease by 50 %. Furthermore, the extraction of groundwater has resulted in an increased seasonal aeration of the wetland located centrally in the catchment. The aeration lead to an oxidation of reduced sulphur bound to the soil layers of the wetland. The sulphur became soluble sulphate, with a subsequent sulphate surge. The result of the experiment was for the wetland and runoff waters an induced acidification. For groundwater in the fractured bedrock, the extraction of groundwater has significantly increased recharge of water from shallow groundwater in glacial till and organic soils and decreased the retention time. These changes have caused the chemical signature of the bedrock groundwater to approach that of the wetland. The result was a deteriorating water quality with increasing concentrations of DOC (dissolved organic carbon) and sulphate, while alkalinity and pH are decreasing.

Time series describing sulphur concentrations and pH in the shallow well (right).



Forest damage caused by air pollution

In the seventies it was noticed that older spruce trees in the Lake Gårdsjön area had lost large numbers of needles. The same thing was happening in Germany, Poland and the former Czechoslovakia, but to an even greater extent. Several explanations were put forward, one being that sulphur and nitrogen pollution were causing the death of the forest, or "Waldsterben", as it was called. Many Swedish and Norwegian researchers found it difficult to believe these theories despite the fact that similar damage but much less severe had been observed in older spruce forest in south-west Sweden and southern Norway.

Crown thinning in spruce has been recorded in the Lake Gårdsjön area. In 1984 a research project was carried out near Lake Gårdsjön (catchment area F3) and it was found that there was extensive loss of needles from the older spruce forest.

Unnatural causes of forest damage

In a study, soil samples were taken for chemical analysis and to examine the fine roots of the trees. It turned out that the entire soil profile, from the surface down to a considerable depth, had become strongly acidic. It was also found that a large proportion of the fine tree roots were dead, and the greater the proportion of dead roots the greater the loss of spruce needles.

Acidification of the soil leads to the loss of calcium, magnesium and potassium, and makes it more difficult for trees to take up phosphorus. Despite this the trees have shown increased growth, due to an increase in the supply of nitrogen from precipitation contaminated with ammonium and nitrate. So the trees are actually growing faster today than 50 years ago, even though their lack of vital nutrients other than nitrogen has never been greater. This puts the trees under stress.

Severe forest decline in spruce forest caused by very high dry deposition of sulphur dioxide (SO_2) to the needles. Photo taken in the Czech republic.

Natural causes of forest damage

The main cause of forest damage is a shortage of water due to drought. Because the trees are bigger now than in the past they also require more water. This means that the general condition of the trees is affected even more in these dry years. Their weakened condition has in turn opened the way for mass infestation by bark beetles over the period 1993-1998.

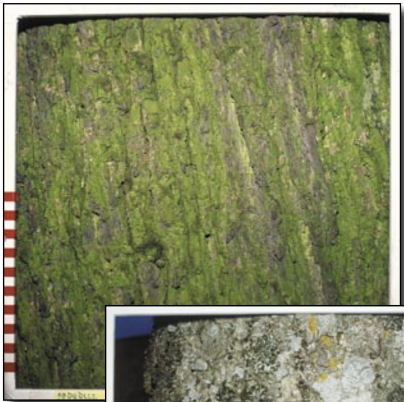
Living candles!

Lack of water is also an indirect cause of the loss of needles and extensive resin leakage. The stem wood shrinks in the drought, the bark separates from the wood and the resulting wound fills with resin. Cracks and small holes in the bark allow the resin to escape through the bark and run down the sides of the trunk. The trees appear to cry!

Lichens and air pollution

Lichen survey to check air quality!

Lichen desert!



Rich lichen flora!

Lichens everywhere

On the ground of the forests around Lake Gårdsjön you will see grey or yellow bushy reindeer lichens and small arch-shaped lichens. Growing on tree trunks you will see variously coloured scabs, leafy rosettes or small bushy growths of lichens. The spruce and birch trees, for example, are covered with a grey coating consisting of several different lichens.

Natural partners

A lichen consists of a fungus that is sheltering an alga. The fungus provides protection and some moisture for the alga, and in return receives nutrient sugars, which the alga produces from sunlight and carbon dioxide. This process is called photosynthesis and is used by all green plants. The self-sufficiency that results from this symbiotic relationship between fungus and alga has made lichens very successful at living in “extreme” environments such as on tree bark or rock.

Partnership also has drawbacks

The process of exchange between the fungus and alga is sensitive to air pollutants, especially sulphur dioxide. Sulphur dioxide forms sulphuric acid, which in turn interferes with photosynthesis in the alga. The alga gradually dies, and without it the fungus of the partnership cannot survive. The entire lichen dies!

Sensitivity to air pollution varies between lichens

The most sensitive of all are bearded lichen, horsetail lichen and lung lichen. If these are plentiful where you live it means that the levels of sulphur dioxide and other pollutants are very low – the air is clean and healthy. On the other hand there are lichens that are relatively tolerant to air pollution. These often thrive when pollution levels rise. One example is *Lecanora conizaeoides*, which is abundant in polluted urban environments. By cataloguing the various lichen and giving each of them a score for sensitivity to pollution it is possible to assess how the lichen community is affected by air pollution.

Why are they so sensitive?

Most lichens are growing very slowly and many species will live for many years. They will therefore be exposed to air pollutions during a long time and different pollutants will accumulate in their thallus. The lack of protecting cuticula is another explanations to why lichens are so sensitive. All different pollutants are accumulated in the thallus.

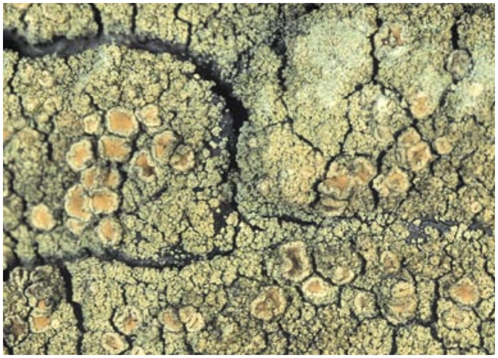
Other types of effects on lichens are caused by acid rain with sulphur and nitrogen. In this case a slow decrease of very sensitive and rare lichens in remote forest ecosystems has been recognized. The relationship between acid rain and effects on lichen vegetation is unfortunalely not so well known, and more research is needed in this subject.

Rich lichen vegetation – indicates good air quality

After decades of increasing pollution levels and decline of lichens, the air quality is slowly improving. There are also some signs that the lichen vegetation is recovering. A national and international engagement in environmental issues has resulted in decreasing levels of sulphur and soot. This is likely to result in a recovery of damaged ecosystems.

Signs of recovery

In small villages as well as in larger towns on the Swedish west coast a recolonization of lichens has been recorded. Sensitive species have been recorded in formely polluted areas and the lichen coverage on treetrunks is increasing. There are also indications of recovery and recolonization of some extremely sensitive lichens, for example *Lobaria pulmonaria*, *L. amplissima*, and *Degelia plumbea*. *Degelia plumbea*, one of the most sensitive species in the Swedish lichen flora, was nearly extinct in the 1980s but is now recorded from at least 150 different localities in south west Sweden.



The pollution tolerant lichen Lecanora conizaeoides.

Beard lichen Usnea filipendula *is sensitive to air pollution and indicates fresh air.*

Lung lichen Lobaria pulmonaria *is very sensitive to air pollution. It has been successfully transplanted on trees in urban areas such as Gothenburg and Stockholm. The experiment shows that recovery of sensitive lichen vegetation in formerly polluted areas is poosible.*

Monitoring the environment – one way of looking into the future

Environmental monitoring at Lake Gårdsjön offers an opportunity to predict the future and gives clear warning signals of whether anything is about to go wrong with our environment. It also shows whether reduced emissions of pollutants have a positive effect on the environment – in other words whether it pays to be environmentally friendly. Information from sites such as Lake Gårdsjön helps politicians make decisions on environmental issues.

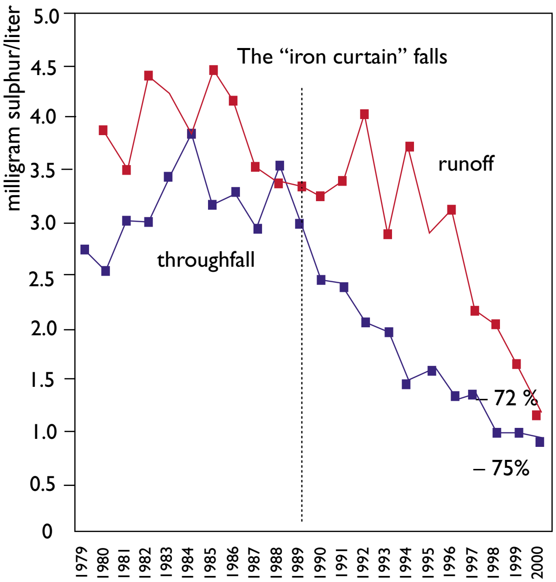
F1 – an environmental fever thermometer

In the little valley that runs to the south there are currently a number of monitoring projects that together build up a picture of how the soil, water, fauna and flora in a small valley behave and react to acid rain and other pollution. Just about everything you see – trees, mosses, lichens and vascular plants – are measured and assessed in a variety of ways. The observations are made at regular intervals. All the information is then processed and evaluated. For example, if a plant shows a sharp decline in numbers then this is reported. The studies on plants and animals are supported by analysis of the water in the small brook, the chemical composition and structure of the forest soil, the decomposition of pine needles and other litter, etc. This whole process of study is called Integrated Monitoring, IM. Integrated Monitoring means that various analyses and observations are carried out on a single site. The monitoring site can be likened to a giant fever thermometer that is used to measure the "health of the environment".

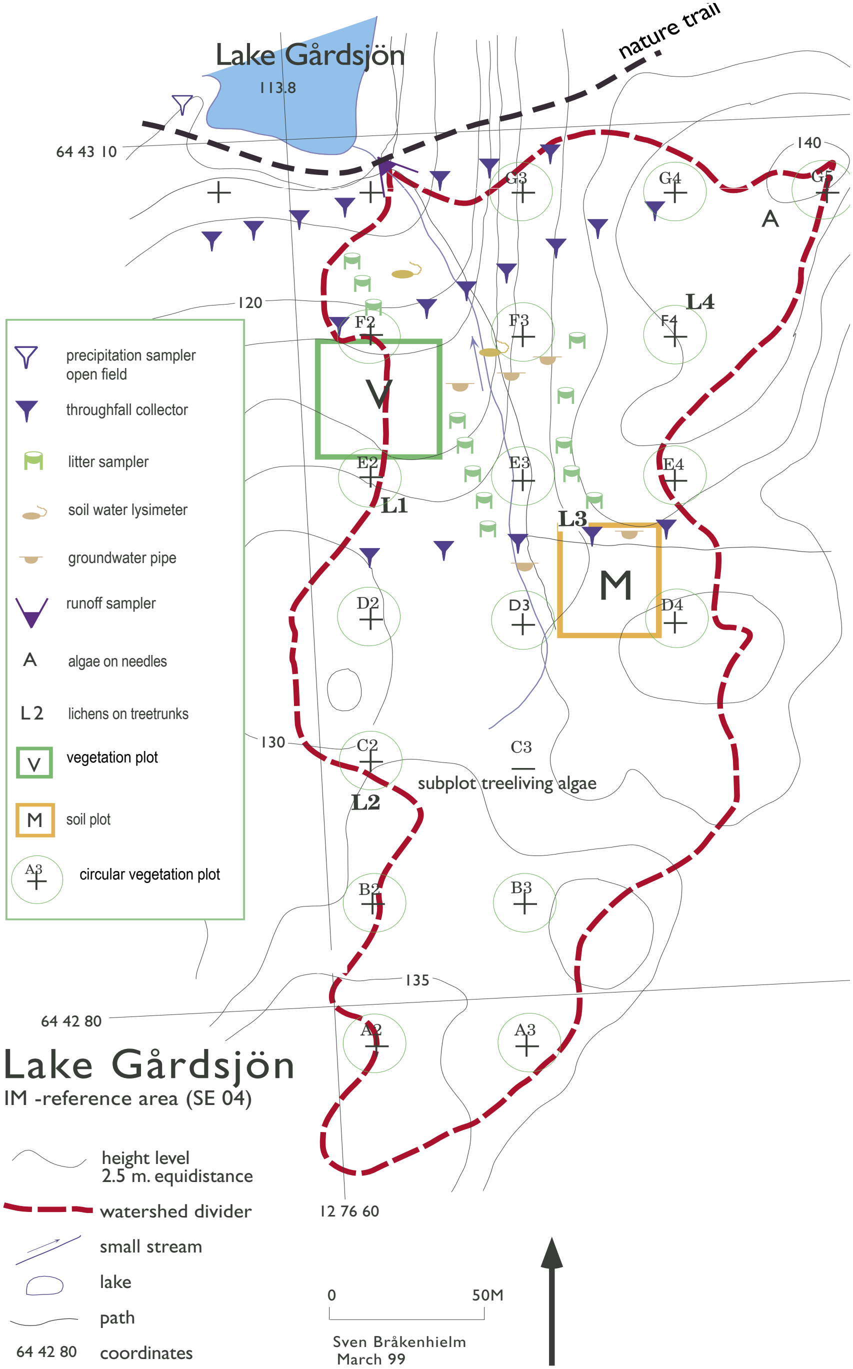
An international project

Monitoring here in area F1 is the responsibility of IVL (the Swedish Environmental Research Institute) and is partly financed by funds from the Swedish Environmental Protection Agency. It is also a part of the European programme for monitoring the effects of reduced sulphur and nitrogen air emissions within the convention on Long Range Transboundary Air Pollution (LRTAP). Monitoring is taking place in more than 20 countries in Europe and North America, and Sweden has contributed four catchment areas: Lake Gårdsjön, Aneboda in Småland, Kindlahöjden in Bergslagen and Gamtratten in Västerbotten. Reports are made annually to the Swedish Environmental Protection Agency and the LRTAP. IVL, SLU (the Swedish University of Agricultural Sciences) and Naturcentrum AB are conducting a variety of projects in the F1 area. This little area therefore plays a very important role in our understanding of environmental impact and natural processes in the world.

In catchment F1 a wide range of environmental variables are measured; soil chemistry, degradation of litter, water quality, tree vitality, moss flora, lichen vegetation and vascular plants.

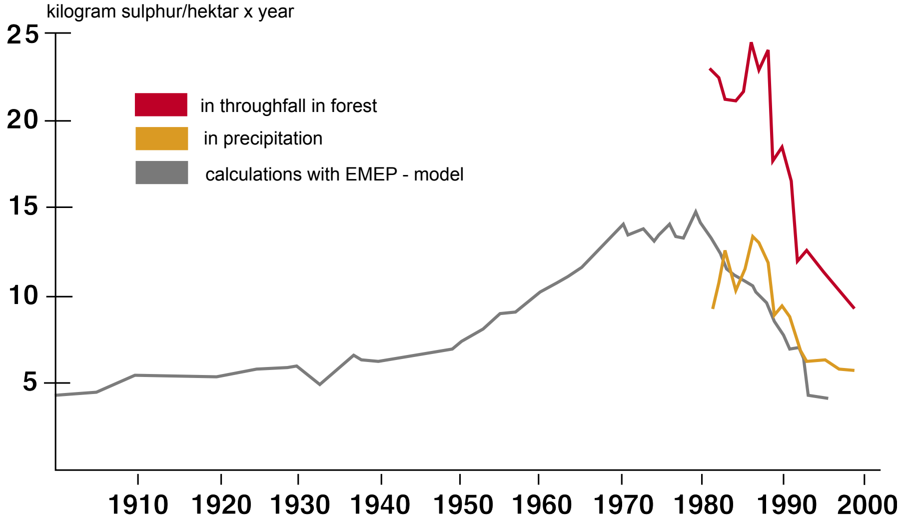


Yearly averaged concentration of sulphur in throughfall and runoff water in the Integrated Monitoring area F1 at Lake Gårdsjön.



Sulphur deposition has occurred at Lake Gårdsjön during 100 years

The graph shows annual sulphur deposition per hectare (100 x 100 metres) during the twentieth century. In the seventies each hectare around Lake Gårdsjön received approximately 15 – 25 kilograms of sulphur every year. The surrounding area (Svartedalen) covers around 30 000 hectares, and over a ten-year period it recieved approximately 7 500 tonnes of concentrated sulphuric acid. In recent years the amount of sulphur in the rain and air has decreased, which is a great relief for the ecosystems. Today we see clear signs of improvements in environmental conditions but the question is whether our damaged ecosystems can recover.

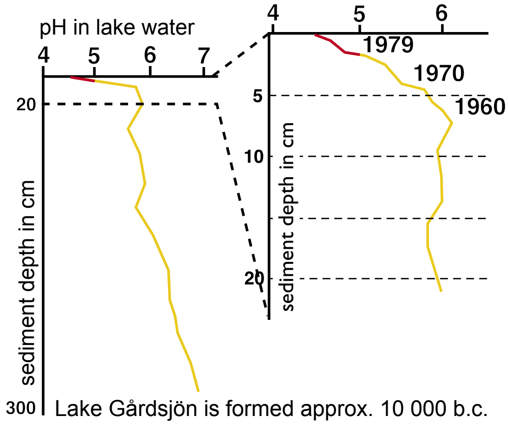


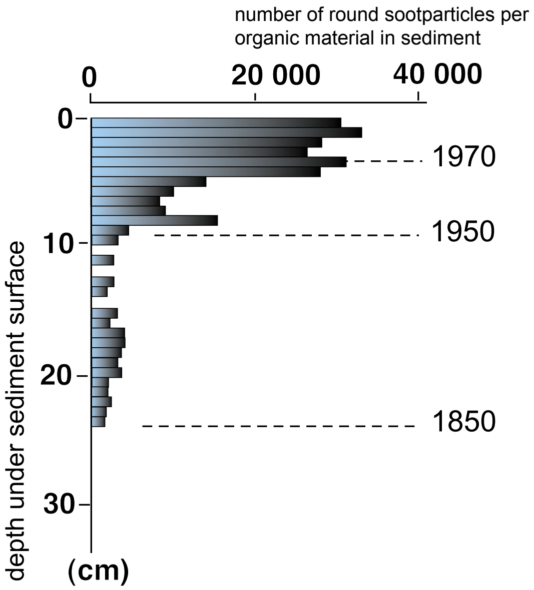
***Throughfall**. When rainwater passes the canopys in a forest chemical species are changed. Sulphur is washed of the needles. Vegetation may also reta*
contains both wet and dry deposition of sulphur.

40 times more acid in 20 years

Studies of the sediment in Lake Gårdsjön show that the pH has decreased from 7 to around 6 during 10 000 years due to natural causes (growth of vegetation, decomposition of organic matter, washout of buffering minerals) and then dropped to around 4.6 between 1960 and 1979, which made the lake 40 times more acidic in 20 years. This drop is a result of anthropogenic air pollutans, primarily sulphur.

Fresh, uncontaminated precipitation has a pH value of 5.6. The rain that falls on Lake Gårdsjön today has a pH of around 4.4. The throughfall is even more acidic. The throughfall is the rain water collected under the trees. It contains the wet and dry deposition of sulphur to the forests. Today the pH in precipitation is increasing as a result of decreased emissions of sulphur in Europe.

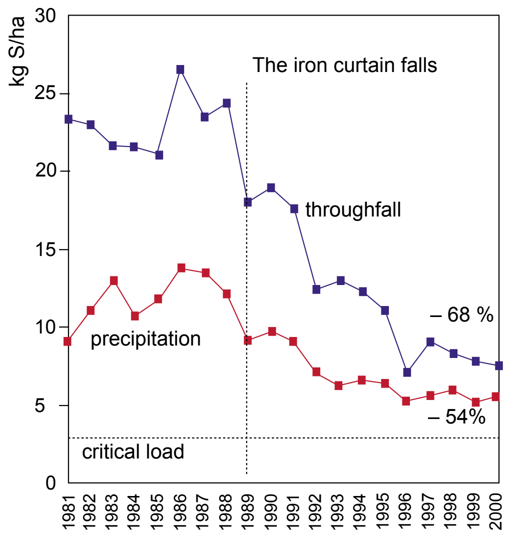




The sediments of Lake Gårdsjön represent a history book of air pollution

In the sediments we can also record the influence of anthropogenic sources by counting the number of sphaeric soot particles. These particles, originating from combustion of coal and oil, first appeared in the nineteenth century. They form a sign of the influence of industrialisation in Europe. It was in the mid-seventies that the concentration of soot reached its peak, as did emissions of sulphur.

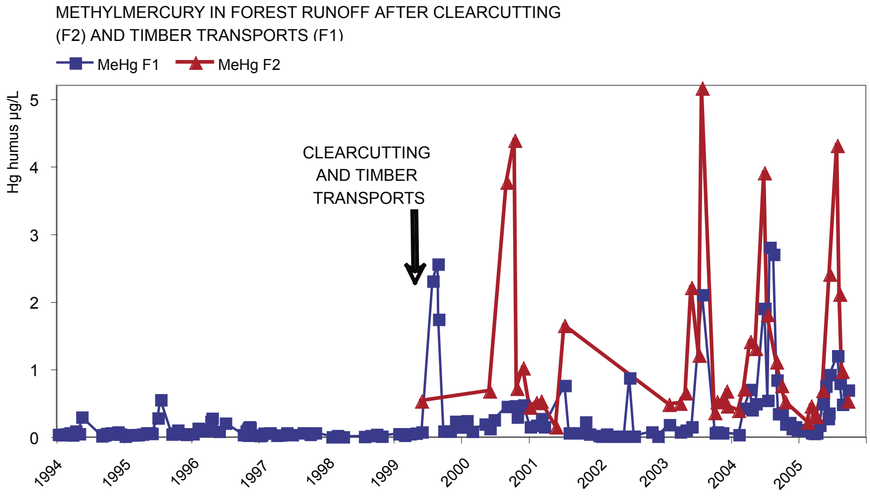
Beginning in the the latter half of the eighties the levels of soot, sulphur and trace metals such as lead and mercury in precipitation all started to fall. By the end of the nineties these levels were about 70 % lower than in the seventies.



Annual deposition by precipitation and throughfall at Gårdsjön during 20 years

The sulphur deposited with precipitation has decreased by 65 % between 1981 and 2001. The throughfall has fallen even more, by 70 % over the same period. The sulphur deposition is higher in the forest due to dry deposition of sulphur dioxide (SO_2) and particles to the tree canopies. The diagram shows that the dry deposition of sulphur has decreased faster than the sulphur deposition by precipitation.

The decrease is caused by large emission reductions in Sweden and the neighbouring countries (mainly Denmark, Poland, Germany and United Kingdom). These reductions are however not sufficient to reach the limits for what the nature can tolerate – the critical load. Many sensitive organisms – fish and other aquatic fauna, lichens etc. will not return until the deposition is below the critical loads. Soil recovery will also take very long.



Methyl mercury increased

Since the summer 1999 very high concentrations of methyl mercury have been observed in runoff water from the long term monitoring catchment (F1). The figure to the right (above) shows that during autumn 1999 methyl mercury concentrations of 2.5 ng L^{-1} were measured in one catchment. These concentrations were up to 50 times higher than the years before. The figure also shows that concentrations of methyl mercury measured in a nearby catchment (F2) during year 2000 were even higher, up to 4.4 ng L^{-1}.

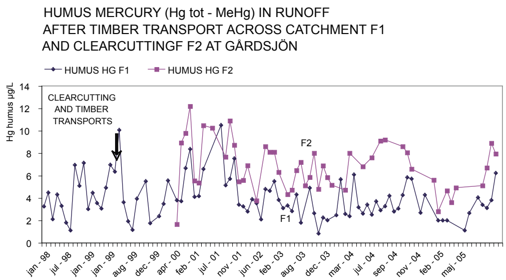
During the years 2000 and 2001 methyl mercury (MeHg) concentrations have decreased in the two catchments but are still much higher than before the summer 1999.

Total mercury increased by about 100 % and decreased to near original concentrations of 2 to 4 ng L^{-1} during 2000 and 2001. Figure to the right (below) illustrates the non methyl mercury or ‘humus mercury (Hg humus)’ shows a small increase at the time of large increase in the concentration of MeHg.

Tractor transport

The high methyl mercury concentrations MeHg in F1 occurred after a clear-felling of the forest in catchment F2. Changes in the hydrology in the valley bottom of catchment F1, where the tractor transport of timber occurred. The tractor caused deep tracks in all parts of the F2 catchment, which caused runoff water in the catchment to run through the upper organic soil horizons. This accident released coloured water with high concentrations of MeHg.

Methyl mercury rapidly increased in the runoff water from the forest soil after driving with heavy vehicles for timber transport over a broke following clear-cutting.



Humus mercury (total mercury minus methyl mercury) is strongly bound to the organic material in the forest soil and did consequently not increase particularly much after timber transport. In contrast to methyl mercury, humus mercury in not toxic and does not accumulate in fish.

Soil pools of mercury

In Sweden organic topsoils in wetlands and forested areas have accumulated mercury and methyl mercury deposited by wet and dry atmospheric deposition over long time periods. Compared to normal atmospheric deposition of mercury it needs thousands of years to explain the large soil pool of mercury.

The soil pool of methyl mercury accounts for some 1 or 2 % of the total soil pool of mercury and may have accumulated for over a much shorter period of time – some 200 to 300 years using today's measurements of atmospheric deposition. MeHg, which to a large degree is bound to low molecular water-soluble fulvic acids, is not bound as strong to the organic matter as Hg humus. MeHg is therefore much more water-soluble than the Hg humus.

Hydrology and methyl mercury

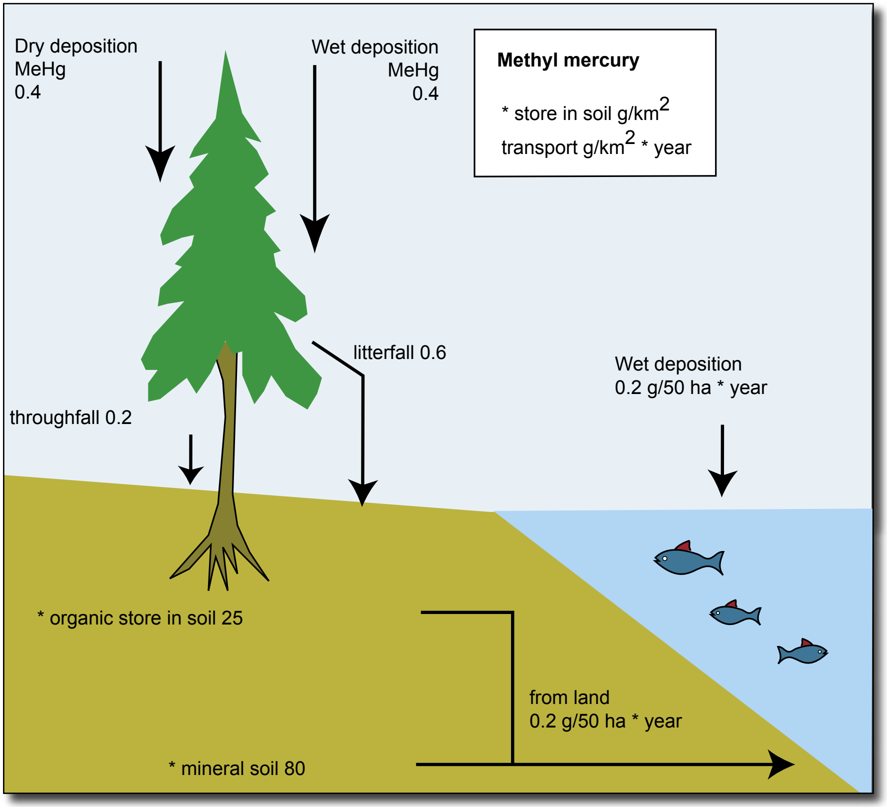
The dramatic effects on hydrology and organic matter in the catchment caused by clearcutting, together with the high water solubility of MeHg may explain the high MeHg fluxes in surface runoff at Gårdsjön during 1999.

Variations in the yearly fluxes of Hg humus are however small and only minor effects were observed on Hg humus as a result of the clear-cutting and timber transports.

Conclusions

Since more than 20 years atmospheric emissions and the use of mercury in industry and in households has decreased in Sweden. MeHg in fish from forest lakes without any direct input of mercury from industry or community has however not decreased at the same rate. Today still some 50 % of all Swedish forest lakes have severe problems with mercury in fish.

One main explanation to this may be that modern forestry, using heavy tractors for timber transports, as well as logging disturbs the humus layer which results in release of the water soluble MeHg from the organic matter. The increased input of MeHg to lakes downstream of logging areas and other forestry practises results in increased bioaccumulation of MeHg in the food chain of lakes with high MeHg concentrations in fish as a result.
Research on additions of low doses of selenium to lakes are performed to reduce the high methyl mercury content in fish in both Sweden and Canada.



Atmospheric inputs, soil storage and output of methyl mercury from forested ecosystems to lakes.

Transboundary air pollution

Many pollutants that are discharged in one country fall on another. The EU has issued directives on reductions of long range transport air pollutants and agreements have been negotiated within UN ECE (United Nations Economic Commossion for Europe). A multi pollution protocol including emission reductions of sulphur, nitrogen oxides, ammonia and volatile organic compounds was adopted in Göteborg in December 1999 (The Gothenburg Protocol). In Sweden sulphur emissions have been reduced by around 80 % since 1980. So can nature and the environment recover? The Forest Roof (6 300 m^2 large catchment) has been an outdoor laboratory to find out whether nature can recover from the effects of acidification in the future. 95 % of all acid deposition, in the form of sulphur and nitrogen, is taken from the Roof catchment and replaced with clean precipitation. Conditions under the roof have been similar to those that existed in Europe before industrialisation, before acidification.

Sulphur and toxic aluminium decrease

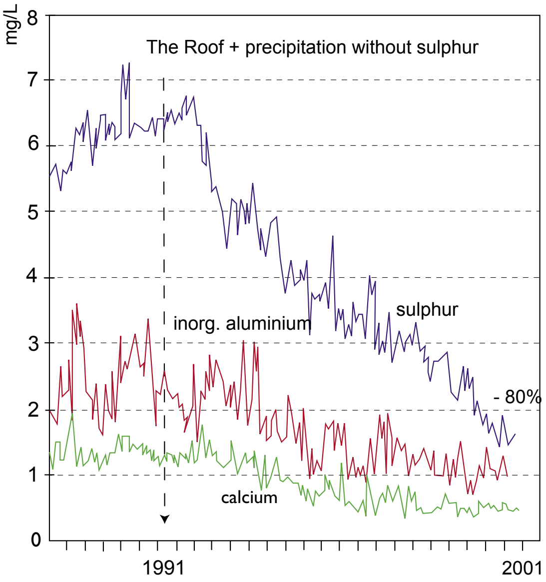
As a result of ten years, from 1991 to 2001, with the roof (the plastic was removed in 2001), the 95 % reduction in acidifying substances to the Roof catchment had several important effects! The concentration of sulphur in the run-off surface water and groundwater had fallen by around 80 %, but the pH value had only risen by a minor 0.1 pH unit. The concentrations of toxic, inorganic aluminium and manganese have decreased at the same rate as sulphur in the run-off water. Unfortunately we have not yet seen any reduction in the levels of mercury and methyl mercury. Despite the strong improvements of water quality the concentrations of calcium, magnesium and potassium in run-off surface water has never been so low. These cations have also decreased at the same rate as sulphur. Plants and animals have never before experienced water that is so low in base cations in this part of Sweden. The liming of lakes must therefore continue even if acid rain stops! The run-off water has increased in color and dissolved organic matter from humus as well as in organic aluminum (not toxic to fish). Opposite to this phosphorus decreased, which resulted in a decreased primary production in lake water (oligotrophication). The cause of this effect remains unclear and needs further research.

Long term recovery

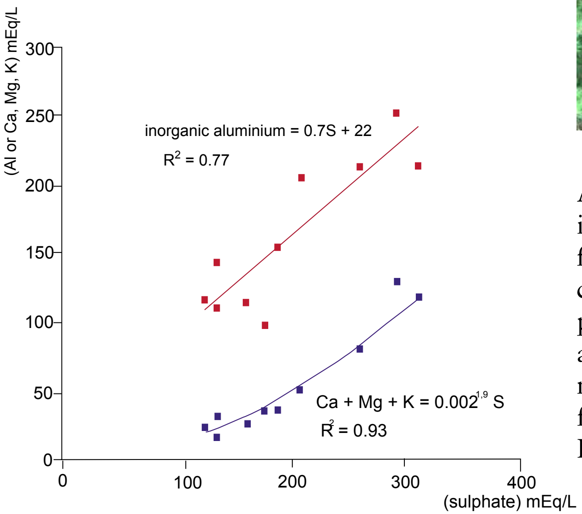
Recovery is expected to take a long time because of the soil´s "memory" of acidification – the sulphur pool is still large, while reserves of base cations (mainly calcium) are practically empty in the acidified soil.

Important questions that the Roof project aimed to answer:

- Does reduced deposition of acidifying substances lead to an improvement in the surface water and groundwater?
- Do concentrations of toxic aluminium compounds in surface water and groundwater decrease? If so, by how much?
- Can fish survive in acidified lakes if the deposition of acidifying substances decreases?
- Will levels of mercury and methyl mercury in surface water decrease when deposition decreases?
- How long will it take before an improvement in water quality can be detected?



The picture on page 39 shows the layout of the experiment in the Roof project. The roof was protecting the catchment from atmosphaeric deposition. The soils and vegetation under the roof were irrigated with water, similar to ”pre-industrial” precipitation. The effects on output of sulphur, inorganic aluminium and calcium by runoff is shown in the figure to the left. A decrease of sulphur by 80 % has been recorded between April 1991 and December 2001. The decrease in sulphur has also resulted in a similar decrease of toxic inorganic aluminium which is good for the survival of fish and other aquatic life. Calcium has also decreased at the same rate which is not good. The decreasing calcium delays the recovery in lakes and streams.



Annual concentrations of base cations (Ca + Mg + K) and inorganic aluminum in runoff water plotted against non marine sulphur in runoff is presented in the figure to the left. It suggests that further decrease in sulphur will result in base cations concentrations close to zero. Inorganic aluminium will however still be present in the future runoff from the forest. The future surface water quality in areas with severe soil acidification will therefore be very different from what was natural before acidification started. Many more results can be studied in a book from the project – ”Experimental Reversal of Acid Rain Effects. The Gårdsjön Roof Project”.

The Swedish research programme ASTA

Two important policy agreements are driving the air pollution control measures in Europe: The Gothenburg Protocol, which entered into force 17th May 2005 and the National Emissions Ceilings Directive, decided upon within the European Union in 2001. Both are aimed for controlling emissions of sulphur dioxide, nitrogen oxides, volatile organic compounds and ammonia by 2010.

These agreements are however not sufficient to reach the long-term objective of no exceedance of critical loads in the whole of Europe. Within the most sensitive areas, e.g. South-West Sweden, Critical loads for acidification will continue to be exceeded. Thus, there are areas where the recovery has not yet started.

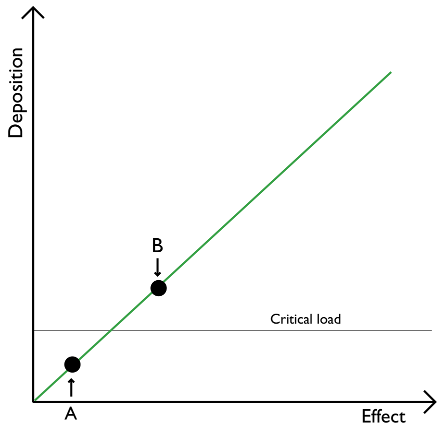
Since a few years the preparation of new decisions has started, primarily through the Clean Air For Europe (CAFE) initiative within the European Commission. This initiative has recently resulted in a Strategy outlining objectives and abatement principles for the period up to 2020.

The period between the signing of the Gothenburg protocol and the today's new policy negotiations have been the time window for the Swedish research programme ASTA to do new supporting research and to develop new concepts and tools for the coming negotiations. The programme is funded by Mistra and has a yearly budget of 10 MSEK.

The research programme includes several new aspects on how to include quantitative understanding of effects into cost-effective control strategies. One of these concepts has been a further development of the Critical Loads concept to include the recovery of acidified lakes and soils by the use of advanced computer simulations.

The Gårdsjön Roof project has been crucial since it has given an immediate indication on how fast recovery will appear in a forested ecosystem when atmospheric deposition is reduced. The Roof experiment has strengthened the models ability to predict future changes and the results have been important for the incorporation of recovery in the present strategies.

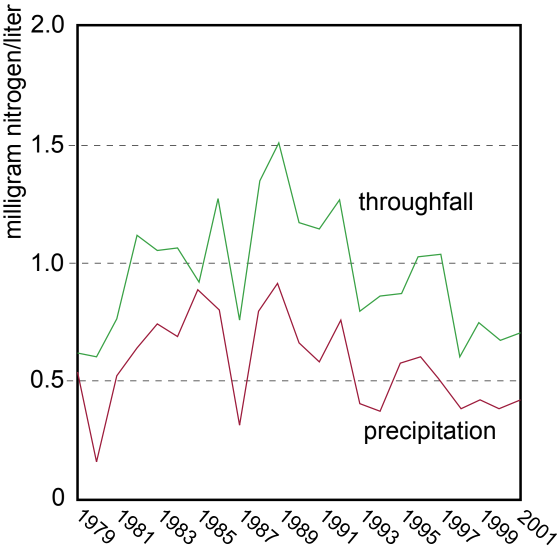
Critical load; principles



A can be described as a ecologically based "goal" because it contains a safety margin

B is a "goal" in which certain negative effects can be accepted, at least in the short term

MISTRA is a foundation funding and organising research aiming for solutions of strategic environmental problems. A MISTRA-programme is considered successful if it has produced high level science, which has become useful in enterprises, authorities of other organisations. The foundation distributes approximately 250 MSEK per year to environmental research. The government of Sweden appoints the board of MISTRA.



Concentrations of nitrogen in precipitation and throughfall during 21 years in Lake Gårdsjön.

ASTA will finish in 2006. During its 8-year period it has taken an active role in transferring scientific knowledge into models and policy understanding through organising workshops, publishing reports and communicating new findings. Lake Gårdsjön has through its appearance and experiments served as one of the best possibilities to communicate the complex processes and effects related to acid deposition.

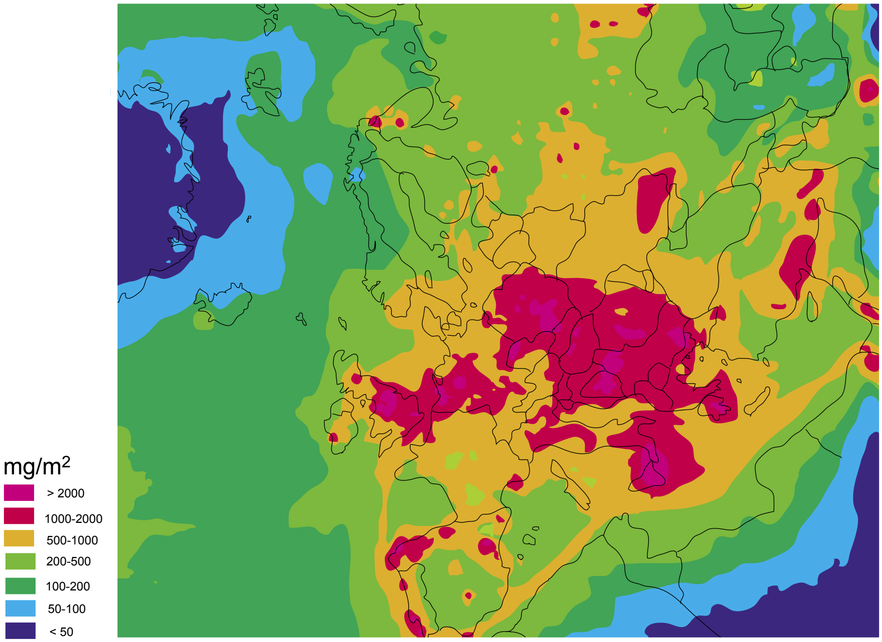
The northern part of lake Gårdsjön with the Gårdsjö cabins.

The ASTA programme focus also on other issues related to transboundary air pollution such as:

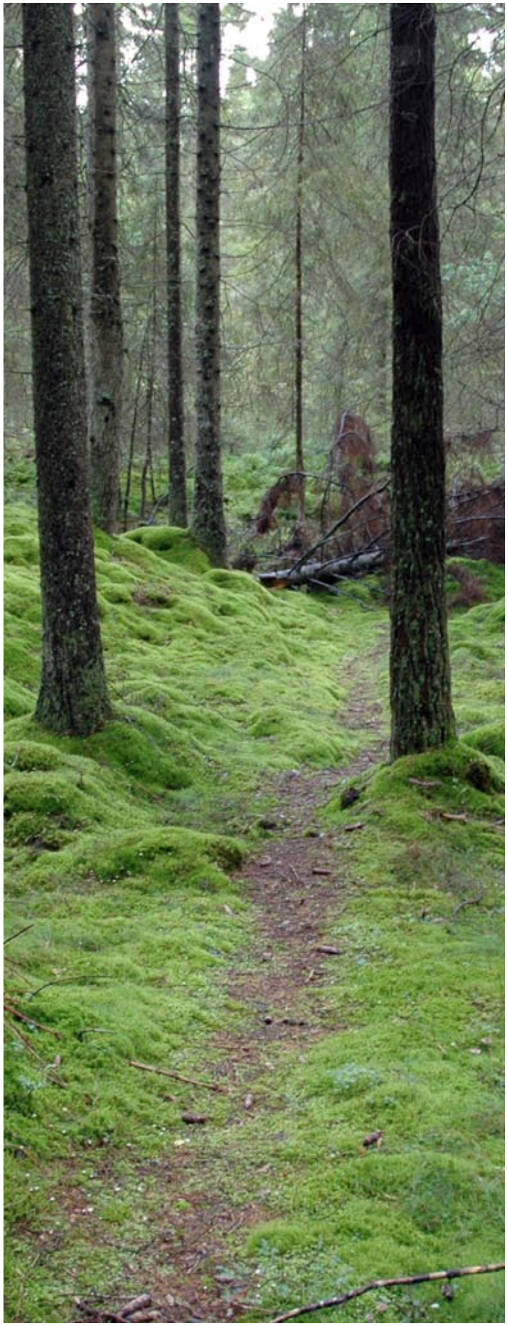
- Effects from excess nitrogen deposition on forested ecosystems. Projects within this area are mainly directed towards changes in biodiversity, improvements in critical loads for nitrogen and to a development of a new model describing how ecosystems change due to nitrogen deposition.

- Ozone effects to agricultural crops and forests. ASTA has promoted the development of more advanced methods for estimating negative effects from ozone. In these methods the ozone effects are adjusted for i.a. variations in climate, light, relative humidity and vegetation structure. The more advanced concepts show that vegetation in N Europe is more sensitive than corresponding vegetation in S Europe due to the more humid climate in N Europe, which leads to a larger uptake of ozone.

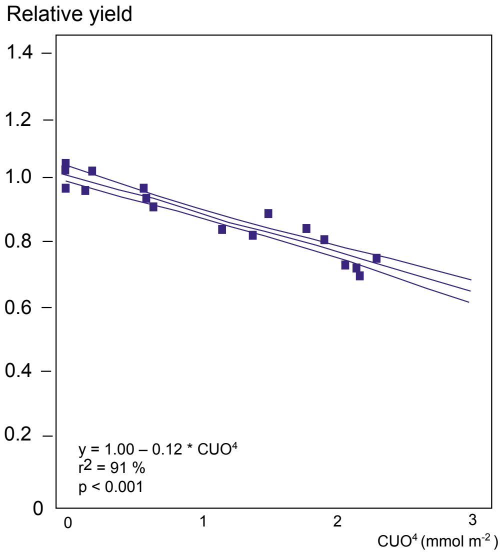
- Characterisation of background concentrations of particles in Scandinavia. Epidemiological studies have shown that particles are causing a large excess in deaths in Europe and the objective of the ASTA project on particles is establish a better understanding of origin and characteristics of the long-range transported particles.



Sulphur depostition in Europe in1999



Ozon, a reactive and dangerous air pollutant



Relative yield of wheat (1 = no effect of ozone) in relation to the accumulated uptake of ozone CUO. The figure '4' in CUO^4 represents that only ozone uptake above a threshold is included.

Ozone exposure experiment performed at the Östad field station outside Gothenburg. In so called open-top chambers the concentrations of gaseous pollutants can be controlled. In this case wheat is exposed to different concentrations of ozone.

Ground-level ozone in the balance

Concerning ground-level ozone a reduction in the concentration can be anticipated as a result of the commitments of the European countries under the Gothenburg Protocol. This could lead to an improved air quality, although the exposure would still exceed the critical levels for ozone in many areas. Furthermore, a major concern in this context is the fact that the background concentrations of ozone over the northern hemisphere are increasing as a result of increasing emissions of ozone precursors – nitrogen oxides and volatile organic compounds – in many countries outside Europe in combination with the intercontinental transport of pollutants for which there is increasing evidence. Possibly, the concentrations of ground-level ozone will increase during the course of the 21^{st} century, regardless of the reduced emissions according to the Gothenburg protocol.

In terms of ozone effects there are some important differences between humans and plants. Humans need to continuously breathe in order to sustain a relatively high base metabolism. Our intake of a pollutant such as ozone is mainly through our lungs. Exercise increases our gas exchange. In addition, children have a higher base metabolism and consequently a larger gas exchange in the relation to body weight. Ozone concentrations tend to be substantially lower indoors than outdoors. Thus, we can influence the ozone uptake in various ways, but our basic gas exchange is high. Therefore, effects of ozone on human health, for which there is strong evidence, is rather directly related to ozone concentrations, which are high in certain parts of southern and middle Europe.

Ozone effects on plants

Plants cannot move in response to environmental change. On the other hand, their gas exchange varies much more than in humans. During the winter it is basically zero. During the growing season, the gas exchange may be large, but only if conditions are favourable. The water balance is crucial for the survival of a plant. In case of dry soil or dry air plants tend to limit their gas exchange by closing their stomata, pores on the leaves which control the gas exchange. Closed stomata prevent carbon dioxide from entering the plant to feed the photosynthesis. Also the pollutant like ozone will stay outside the plants, while water loss is minimised. A consequence of this is that in dry climates, like a large part of the year in the Mediterranean, ozone uptake by plants will somtimes be relatively small despite sometimes rather high ozone concentrations. In more humid parts of Europe, such as south-west Sweden the ozone uptake can be large although ozone concentrations are not extremely high.

Air pollution, acidification and future

The Gothenburg protocol

In many respects the European cooperation to combat transboundary air pollution can be viewed as a success. In particular this holds for sulphur. This cooperation got a major impetus when the Convention on Long-Range Transboundary Air Pollution (CLRTAP) was signed by a large number of countries in 1979. The convention is based on a number of so called protocols in which emission reduction for different pollutants in specified. In December 1999 the most complex and far-reaching, the so called Gothenburg protocol was signed. This treaty covers four different pollutants (sulphur dioxide, nitrogen oxides, volatile organic compounds and ammonia) and three major environmental problems (acidification, eutrophication and ground-level ozone).

According to this protocol, the sulphur emissions of Europe are to be reduced by 62% between 1990 and 2010. For the 15 countries that were members of the EU in 1999 the reductions was set at no less than 75%. In many countries, such as Sweden, the sulphur emissions were reduced considerably already during the 1980s. Consequently, in relation to the situation when the sulphur emissions were at maximum, a very large decrease in sulphur pollution is underway. The Gothenburg protocol was ratified and entered into force in 2005.

The Gothenburg protocol covers emissions of for instance volatile organic compounds and nitrogen oxides, both of which have traffic as the largest source. In combination with solar radiation these pollutants form ozone.

Improvement underway

Since sulphur is the dominating pollutant behind acidification in most areas, the Gothenburg protocol is a major step forward. Large areas of Europe, including parts of Sweden, will slip out of the shadow of acidification and will start to recover. However, also with the substantial reductions of pollution emission stipulated by the Gothenburg protocol, some areas, such as parts of south-west Sweden, and possibly high precipitation areas of the mountain range, will still suffer from continued acidification. Also, the relative importance for acidification of nitrogen pollutants, and of the biomass harvest of forestry, is expected to increase in the future.

Ozone injury, necrotic spots, on clover leaves.

Recovery

Our understanding of the recovery process from acidification is limited. The studies performed in the Roof project at Lake Gårdsjön indicate that the quality of the out-flowing groundwater from acidified forest soils, will improve relatively fast upon substantial reductions in acid deposition. Regarding the state of the acidified forest soils it seems that the recovery proceeds conside-

The Swedish National Environmental Objectives

'To the next generation we should be able to hand over a society where the major environmental problems are solved. The fifteen environmental quality objectives shall lead the way for our efforts to achieve an ecologically sustainable development of the society. They have become the focus of all Swedish environmental work, regardless of where or by whom it is undertaken.'

The objectives are:

- Reduced Climate Impact
- Clean Air
- Natural Acidification Only
- A Non-Toxic Environment
- A Protective Ozone Layer
- A Safe Radiation Environment
- Zero Eutrophication
- Flourishing Lakes and Streams
- Good-Quality Groundwater
- A Balanced Marine Environment
- Flourishing Coastal Areas and Archipelagos
- Thriving Wetlands
- Sustainable Forests
- A Varied Agricultural Landscape
- A Magnificent Mountain Landscape
- A Good Built Environment

rably slower. Maybe this process will take several decades or even longer, if a complete recovery is at all possible in all areas. Without doubt there will be a chemical memory of the period of severe acidification 1950-2000 in large areas of forest soil far into the future.

The Swedish environmental objective "Natural acidification only"

As part of the national work with so called "environmental objectives" goals for acidification have been set: in 2010 no more than 5% of Swedish lakes and 15% of the running water should be suffering from man-made acidification. These figures can be compared with the statistics saying that in 1990 more than 15% of the lakes were acidified and approximately one third of the running waters were affected by acidification. In south-west Sweden more than every second lake was acidified at this point. These figures would have been even higher had liming not been used to temporarily counteract acidification. In year 2000 approximately 7 500 lakes and 11 000 km running water were limed.

Liming of forest soils

Liming of forest soils in southern Sweden is currently under discussion. In 1999 somewhere around 50 000 ha of forest soils had been limed on a test basis. There is now a pressure to use forest liming on a larger scale, in particular in the most acidified areas of southern Sweden (Götaland). Forest liming can be designed to add also nutrient base cat ions such as calcium, magnesium and potassium, which have been washed out of the soil as a result of acidification.

Liming of forest soils is more controversial than liming of surface waters. The reason is that many organisms, such as mosses and lichens, can be severely damaged by liming, especially if fine grains of lime are used. In lakes and running waters the inadvertent or negative effects of liming have been small or modest, while the positive effects on fish stock and other organisms have been considerable.

Ammonia from agriculture – an unsolved problem

The Gothenburg protocol covers, apart from sulphur, also volatile organic compounds, nitrogen oxides and ammonia. The first two have important direct effects on man and ecosystems, but, perhaps more importantly, they form ground-level ozone when exposed to solar radiation. According to the protocol a reduction of 45% has been agreed upon, while the corresponding figure for nitrogen oxides is 40%. Some countries seem, however, to have large problems in meeting their commitments for nitrogen oxides under the Gothenburg protocol.

Nitrogen oxides contribute not only to ozone formation, but also to acidification and eutrophication. Another nitrogen compound, ammonia, is of equal importance for these problems, but does not form ozone. Ammonia originates largely from animal raising in agriculture. The agreed reduction under the Gothenburg protocol is only 18%. Over large areas of Europe, especially those with intensive agriculture, ammonia will continue to be an important environmental problem. There is also a substantial long-range transport of ammonia over the continent.

Health effects are now in the main focus of interest in the air pollution debate. Especially fine particles are considered to be harmful, partly also ground-level ozone.

Human health – a major concern from air pollution

Health effects have become a dominating issue in the European discussion of air pollutants and their effects. Especially there is great concern for the effects of fine particles on longevity and illness in humans. Fine particles have different sources and can also form from other pollutants in the atmosphere. They are subject to long-range transport and therefore constitute an international problem, the seriousness for which there is increasing evidence. Also ground-level ozone can have serious health effects.

The Gothenburg protocol does not solve everything

Even if the countries of Europe will comply with their commitments under the Gothenburg protocol, there will still remain important air pollution problems, including fine particles, ozone and the still very large deposition of nitrogen. Currently, nitrogen, added through pollution deposition, is accumulated in many ecosystems. Such accumulation will continue in many areas also when the rather modest decreases in nitrogen emissions of the Gothenburg protocol have been implemented. Most likely, this will lead to increasing effects of nitrogen on species composition as well as soil and water chemistry over large areas in the decades to come.

The dominating cause of air pollution and acidification is the use of fossil fuels. A successive transfer of the energy system towards renewable energy sources such as wind, solar panels and solar cells, biofuels and different types of hydropower is the best solution of this problem, along with reductions in the total energy turnover of the society based on efficiency and smart solutions.

Literature & home pages

Home pages

www.gardsjon.org
www.forsurning.nu (The NGO Secretariat on Acid Rain)
www.snf.se/verksamhet/forsurning/index.cfm (Swedish Society for Nature Conservation)
www.environ.se (Swedish Environmental Protection Agency)
www.unece.org/env/lrtap/ (The LRTAP Convention)
www.europa.eu.int/comm/environment/air/index.htm (EU Comission, DG Environment)
www.asta.ivl.se (The ASTA programme)

The Gårdsjö Foundation

is a non profit foundation of 1991 initiated by the Hensbacka foundation, the Swedish Environmental Research Institute and the municipality of Stenungsund. The board includes representatives from the County Adminitration of Västra Götaland, the Forestry County Board, the Hensbacka foundation, Swedish Environmental Research Institute, the Swedish NGO Secretariat on Acid Rain, the municipality of Stenungsund and the Chemical Industries of Stenungsund.

The Role of the Gårdsjö Foundation

is to distribute information on air pollution and acidification effects on water, forest and land to decision makers in society, environmental experts within private and public sectors, political and non-profit organisations, schools, researchers and the general public, both nationally and internationally. The work is based on reseach carried out at Lake Gårdsjön.

Further reading

Effects of Nitrogen Deposition on Forest Ecosystems (2000). Bertills, U. and Näsholm, T. (eds.) Rapport 5067. Swedish Environmental Protection Agency.

Experimental Reversal of Acid Rain Effects. The Gårdsjön Roof Project (1998). H. Hultberg & R. Skeffington. Wiley & Sons. 466 sidor.

Lake Gårdsjön. An acid forest lake and its catchment (1985). F. Andersson & B. Olsson. Ecological Bulletins 37. Stockholm. 336 sidor.

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Ground-level ozone – a threat to vegetation (1999). H. Pleijel (ed). Report 4970. Swedish Environmental Protection Agency.

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The Earth is 4.5 billion years old. The bedrock around Lake Gårdsjön, the gneisses and the granites, are 1.7 billion years old. The last glaciation is not more than 12.000 years away. Thus, soils in the forests around Lake Gårdsjön are relatively young from a geological perspective. The soils are also very thin and has a poor buffering capacity. That is why air pollution in the last decades have had such a large impact on water and soil ecosystems around Lake Gårdsjön. This holds also for thousands of other lakes in Sweden and other countries on the Northern Hemisphere. During a very short period in the history of the earth, less than 100 yeras, the ecosystems, groundwaters and lakes have changed under the impact of acidification.

But, since the 1980s, air pollutants, especially sulphur dioxide, has decreased dramatically. This has resulted in a slow recovery of the ecosystems over much of the acidified land area in northern Europe.

There are, however, still importand environmental concerns. The nitrogen deposition is too high, as well as the concentrations of ground-level ozone.

In this booklet the results of 30 years of research on the effects of acidification are presented. It also gives a brief presentation of the most important envirionmental issues that related to ecosystems, soils, water and lakes, with lot of examples from the Lake Gårdsjön area.