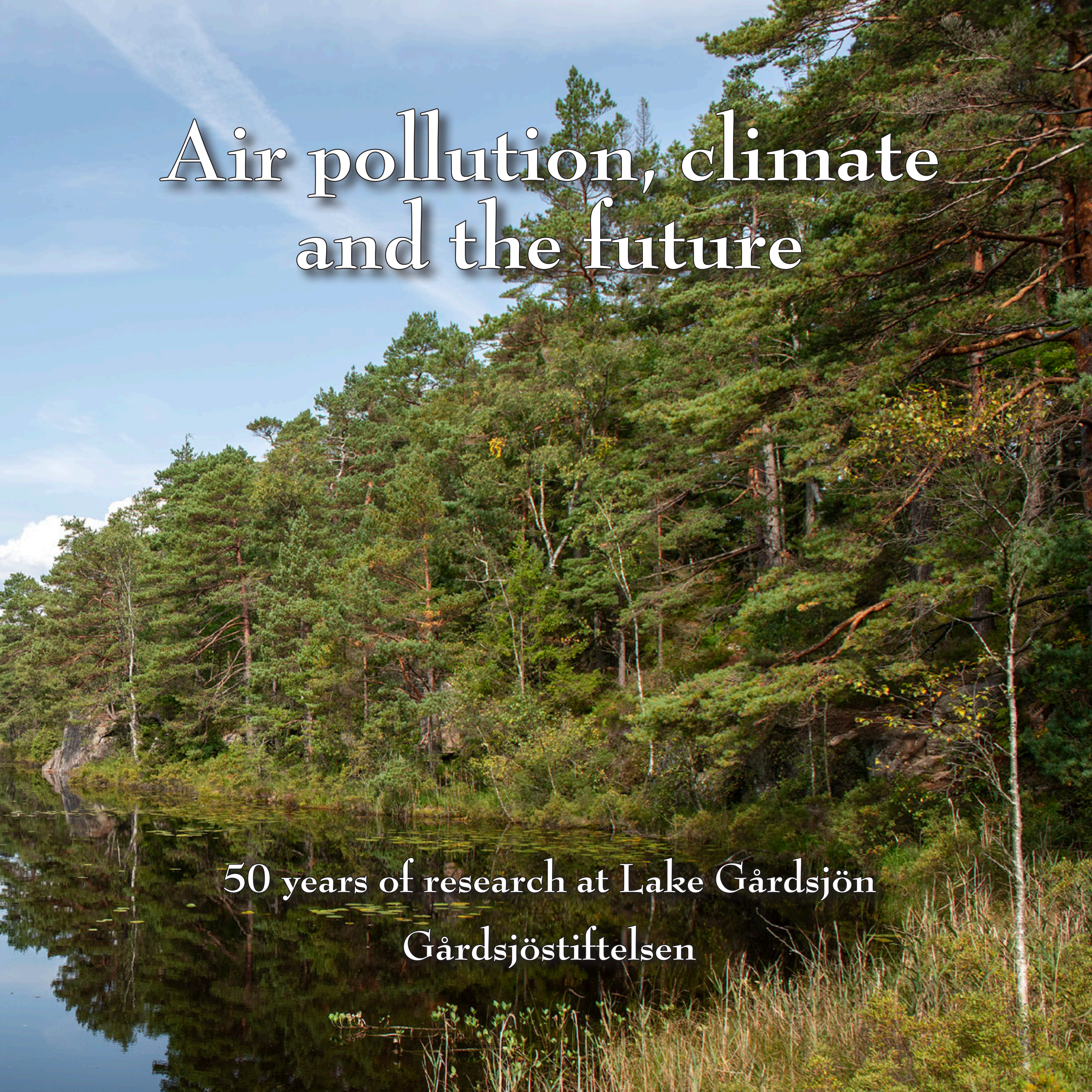

Air pollution, climate and the future

50 years of research at Lake Gårdsjön

Gårdsjöstiftelsen

Air pollution, climate and the future

This book should be cited as follows: Gårdsjöstiftelsen 2023. *Air pollution, climate and the future. 50 years of research at Lake Gårdsjön.* – Gårdsjöstiftelsen.

Articles:

Welcome to Gårdsjön and its flora and fauna. Svante Hultengren, Naturcentrum AB.

The lakes in the Svartedalen area. Ragnar Lagergren, County Administrative Board of Västra Götaland.

Nitrogen in the forest. Sara Jutterström and Filip Moldan, IVL Svenska Miljöinstitutet AB.

Monitoring the environment. Sara Jutterström and Filip Moldan, IVL Svenska Miljöinstitutet AB, Ragnar Lagergren, County Administrative Board of Västra Götaland and Håkan Pleijel, University of Gothenburg.

Air pollution and acidification – 50 years of transboundary air quality policy. Christer Ågren.

Climate, air pollution and landscape. Håkan Pleijel, University of Gothenburg.

The mercury problem in Sweden and at Gårdsjön. Hans Hultberg, Sara Jutterström and John Munthe, IVL Svenska Miljöinstitutet AB.

Technical editing, layout and production: Svante Hultengren, Naturcentrum AB.

Translation: Seven G translations.

Photos: Claes Andrén (smooth snake p.15), Sven Birkedal (greater butterfly orchid p. 15), Ragnar Lagergren (Torrgårdsvattnet and Härsvatten p. 18 and 20), Thomas Liebig (bog asphodel and creeping lady's tresses p. 10), Filip Moldan (p. 51), Håkan Pleijel (p. 29, 30, 32, 33 tobacco leaf, 34 lungwort, 37, 48 spruce forest), Henrik Weibull (greater fork moss, common haircap and papillose peatmoss p.16) and Christer Ågren (p. 40). Other photos: Svante Hultengren.

Illustrations: Klaus Albrechtsen (p. 37), Nils Forshed (p. 11 and 48), Svante Hultengren (phantom midge larva and water boatman p. 19) and Therese Johannesson (perch p. 19).

Map: Metria, Ortofoto.

Printing information: 500 copies, Elanders AB.

This book can be ordered from: Gårdsjöstiftelsen, c/o Naturcentrum AB, Västanvindsgatan 8, 444 30 Stenungsund, Sweden, email: ncab@naturcentrum.se

ISBN 978-91-85221-49-3

This book was printed with financial support from The Swedish Environmental Protection Agency, Lokala Naturvårdssatsningen (LONA) and Naturcentrum AB.

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50 years of research at Lake Gårdsjön

– Gårdsjöstiftelsen –

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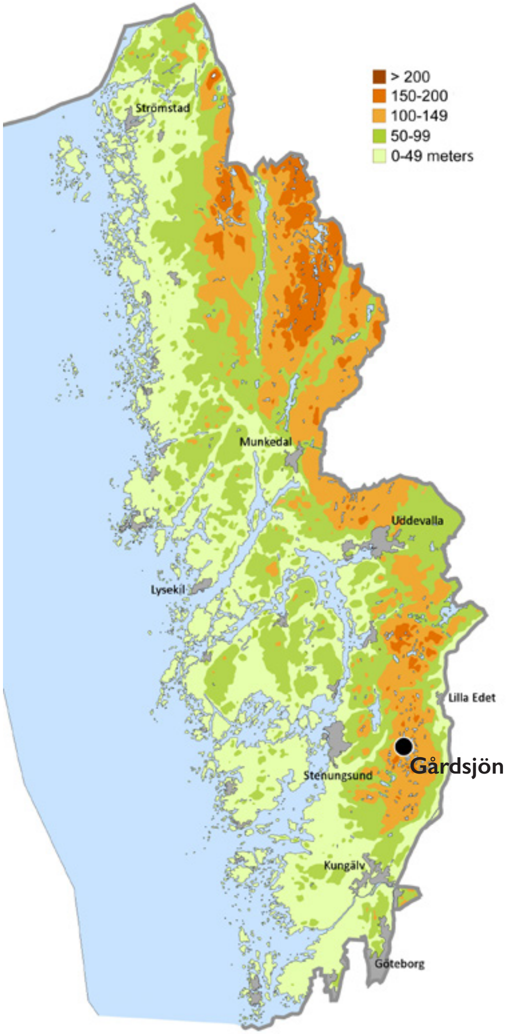
Welcome to Gårdsjön



Gårdsjön is located about 50 km north of Gothenburg. Head north on the E6, and take the Ucklum exit at Stora Höga. Drive a further 9 km north to Ucklum. In Ucklum, take the turning for Västerlanda. After about 4 km turn right towards Gårdsjön. Welcome!

Gårdsjön is a clear-water lake around 32 hectares in area, located in nutrient-poor moraine landscape about 10 kilometres east of Stenungsund in the province of Bohuslän. The lake is part of the River Anrås water system which flows into the sea near Anrås in Stora Höga. The surrounding forest area is called Svartedalen and extends a few tens of kilometres to the south. The bedrock around Gårdsjön consists of slow-weathering gneiss and granite, and the soils are dominated by moraines. During the 1960s there were extensive fish deaths in the lakes and waterways of south-western Sweden. A combination of heavy acid rain and soils that have low resistance to acidification meant that the lakes in Svartedalen were particularly hard hit.

Research around Gårdsjön

Research has been conducted in and around Gårdsjön for the past 50 years on air pollution and its effects on water, flora and fauna. This has led to a wealth of scientific papers and significant books on acidification and other environmental impacts. Many of the results of this research have broken new ground and helped to clarify the links between acid rain and its effects on water, soil and ecosystems. The results have informed decisions by policy makers, from local to EU level, on how acidification and other air quality problems can be tackled.

Nature trail and information book

A nature trail was created in 2000 to inform visitors about Gårdsjön's various research projects and its flora and fauna. This trail has become very popular, and in 2023 the trail, boardwalks and signs were updated. The nature trail starts between the car park and the lake and offers a diverse walk about 5 kilometres in length around the entire lake (see map on page 8).

In 2007, Gårdsjöstiftelsen produced a book about Gårdsjön that summarised the results of 35 years of research around the lake. It also included insights from the rest of Sweden, Europe and the world in general. We can now add a further 15 years of experience to this tale of the environment and the long research initiative. This book is the result of that work.

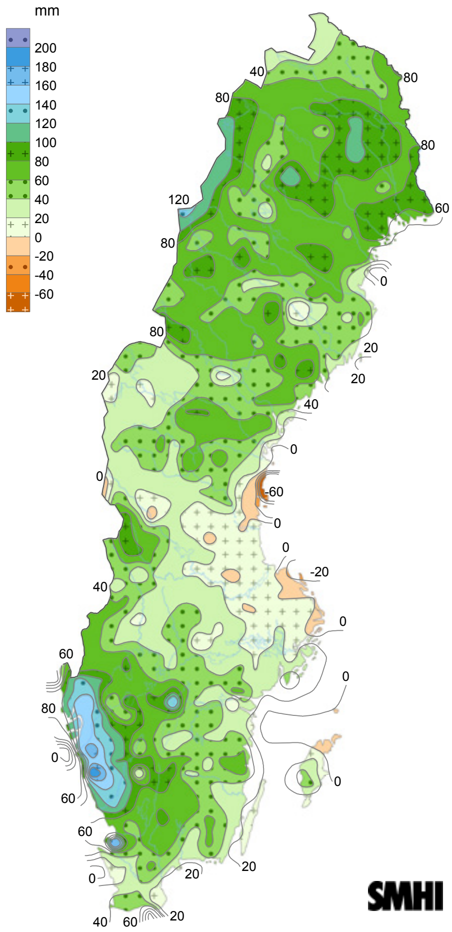
Nature at Gårdsjön

Afternoon clouds towering over Gårdsjön.

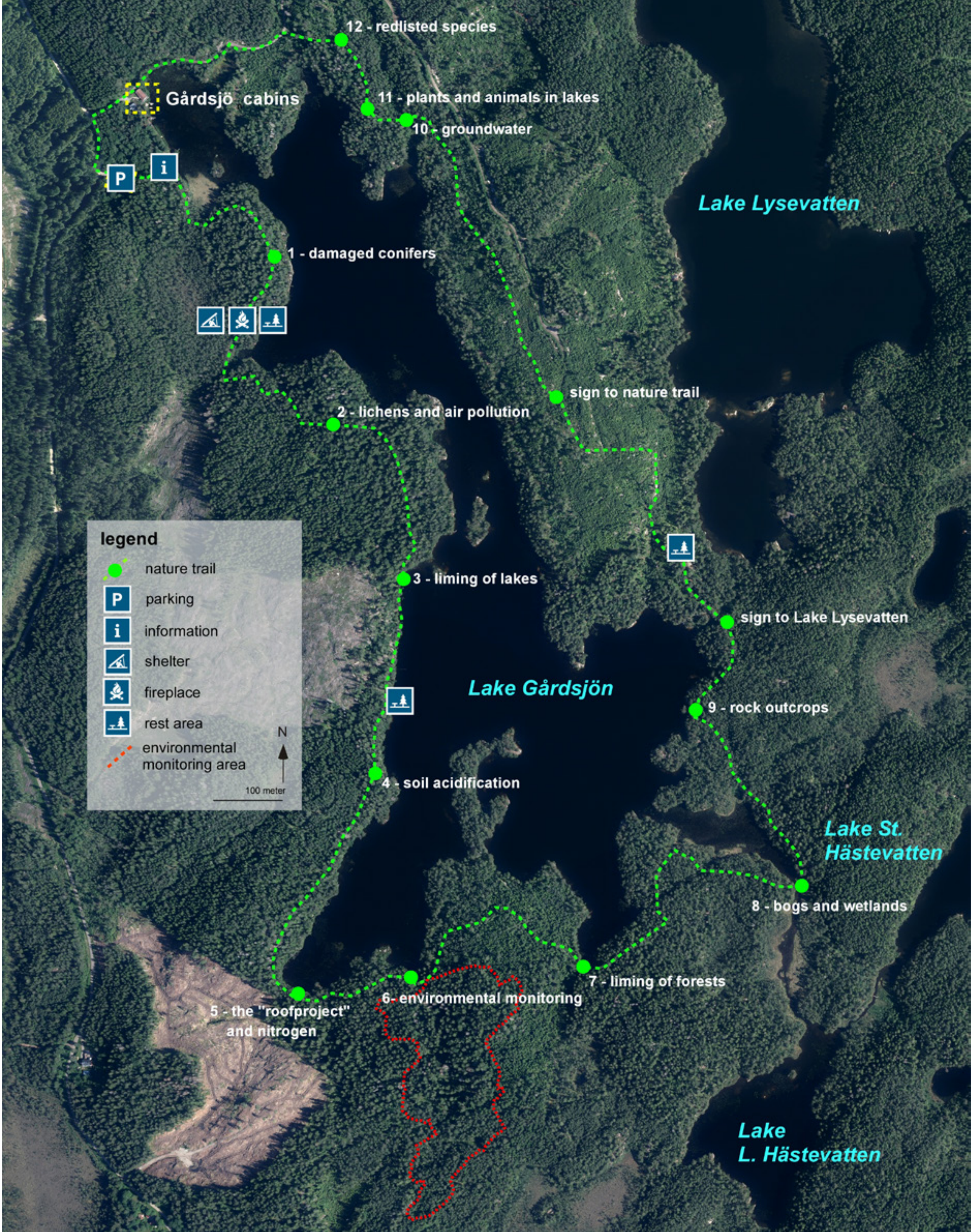
The climate

No other Swedish province is so closely associated with the sea as Bohuslän, and this closeness has a moderating effect on the climate, especially the temperature. In the upland eastern parts of the province, the average temperature in February (the coldest month) is just below -1°, while at the coast it is closer to +1°. In July, the average temperature in the province is around 17°. These values are for the reference period 1991–2000.

Annual precipitation ranges from about 600 mm for the outermost coastal islands to just over 1000 mm inland. At Gårdsjön, one of the wettest parts of Bohuslän, it is up to 1200 mm/year. The increased rainfall is due to moist air from the sea being pushed up over the mountains, causing the moisture in the air to cool, condense and fall as rain. This phenomenon is known as orographic precipitation after the Greek word "oros" meaning mountain. Like the rest of Sweden, Bohuslän has become warmer in recent years. Precipitation has also increased, particularly in the area stretching from northern Halland to inland Bohuslän.



There has been a large increase in precipitation throughout most of Sweden. The largest increase has occurred on the west coast of Sweden. The map shows differences in precipitation (mm/year) between the periods 1961–1990 and 1991–2020.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Rock outcrops – nutrient-rich but species-poor

Gårdsjön is surrounded by various types of forest but dominated by trees on a thin layer of soil between rocky outcrops. With their sparse pine trees, thin soil cover and scattered tufts of heather these appear at first glance to be straggly and species-poor. You might even wonder how large trees can grow on such soil at all. But despite the stark appearance, there are actually quite a variety of organisms living here.

Look a little closer

The rock outcrops appear the barest of all, but this is just an illusion. In fact, the rock surfaces are covered with a mosaic of various crustose and foliose lichens. Hundreds of lichens live on the nutrient-poor rock surfaces. These lichens cover almost 100 percent of the rock surfaces and help to erode and break down the rock.

Lichens are composite organisms made up of algae, bacteria and one or more fungi. They are actually more like tiny ecosystems than individual species. The fungi are the dominant, most visible, component, but inside the lichen are algae that use photosynthesis to create carbohydrates. These are eaten by the fungi, which in return protect the algae inside the fungal body. This makes lichens relatively hardy, so they can grow in places where no other organisms survive, like the rock outcrops around Gårdsjön. They can grow on these rocky surfaces with little competition from plants. Most lichens grow extremely slowly. Reindeer lichens *Cladonia* spp., for example, only grows half a centimetre per year and needs tiny amounts of nutrients and water, while map lichen only grow a tenth of a millimetre per year.

There are very few broadleaf trees and herbaceous plants because the soil is poor in nutrients and the thin soil dries out easily. But you can find heather, occasional moss tufts, rock campion, hair grass and sheep fescue on the rocky outcrops. Here and there, where water gathers, pine seedlings sprout and create sparse tree cover.

More soil – more plants

Where soil has gathered, often in damp hollows, other green plants can take hold. The dense, shady spruce forest is dominated by large broom moss, glittering wood moss, red-stemmed feather moss and blunt-leaved bogmoss. Dense tufts of matt-green pincushion moss can also be seen here and there. Page 16 shows a number of common moss species from the Gårdsjön area. The soil is often a little deeper where mosses cover larger areas, and purple moor grass, blueberry and lingonberry can be found in forest glades.

Cross-leaved heath *Erica tetralix* (above), bog asphodel *Narthecium ossifragum* (below) and creeping lady's tresses *Goodyera repens* (below).

Mires, bogs and fens

The heavy rainfall and characteristic fissure valley landscape mean that Gårdsjön and Svartedalen have many small, elongated lakes, streams and wetlands.

Soil, rock and plant and animal remains all gather at the bottom of the lake. Over time, the lake slowly fills with these deposits. As it becomes shallower it turns into a fen, and in areas of heavy rainfall areas with nutrient-poor, acidic soil it develops into bogs. Perhaps Gårdsjön will turn into a mire in the future.

A mire is a collective term for bogs, fens and transition mires. Bogs are large wetlands covered with sedges and bog mosses *Sphagnum* spp. that only receive water from precipitation. A bog is very poor in nutrients, as the only nutrients that reach the raised bog come from rain and snow.

Fens, on the other hand, receive water with varying levels of nutrients from the surrounding land. Fens are classified as poor, intermediate or rich, depending on the availability of minerals, mainly chalk, in the feed water. The fens around Gårdsjön are all nutrient-poor. Many bogs are surrounded by a circular fen. These are sometimes known as a lagg or lagg fen. The flora in the lagg fen is often more diverse than in the bog. The Gårdsjön area has many small mires with narrow borders of lagg fen.

Bog mosses dominate the bogs. These mosses grow on top, but die at the base, and the dead mosses raises the bog. The dead plant matter in the bog is called peat. Most bog moss species thrive in low pH and low nutrient levels, and they are actually rare in chalky areas such as Öland and Gotland, and much of the rest of Europe. Around 15 species of bog moss have been recorded among the mosses in the wetlands around Gårdsjön, including Girgensohn's bog moss *Sphagnum girgensohnii*, spiky bog moss *S. squarrosum*, blunt-leaved bog moss *S. palustre* and Magellanic bog moss *S. magellanicum*. See photos on page 16. Nitrogen deposition and drainage have led to changes in the vegetation of many bogs, such as favouring the growth of the small Scots pine.

Oceanic plants

Along the stream towards Lilla Hästevattnet, south of Gårdsjön, there is a mix of fen- and bog-loving vegetation. It is home to several species of bog mosses, common reed, cranberry, bog rosemary, bog myrtle, cross-leaved heath and the beautiful yellow bog asphodel, *Narthecium ossifragum*. This asphodel is only common in south-western Sweden and western Jämtland, where the climate is more humid. It flowers in late summer to autumn and its Latin name comes from the belief that it caused brittle bones in goats. In eastern Sweden, wild rosemary, *Ledum palustre*, is a common sight on mires, but it is largely absent from western Sweden.

Other coast-tolerant species around Gårdsjön include the already mentioned cross-leaved heath and bog asphodel. Both thrive in fens and wet mires. Cross-leaved heath is closely related to common heather but has larger and plumper pink flowers. Another, less common coast-tolerant plant is the slender St John's wort, *Hypericum pulchrum*, which can be seen in several places around Gårdsjön. It generally grows on grazed open moors. Slender St John's wort is mainly found in central Bohuslän and is considered a remnant of the time when the area was covered by open or semi-open grazed moorland, more than 100 years ago. Curiously, the seeds of this species seem to be roused from dormancy by soil disturbance, for example along road and logging tracks. Slender St John's wort is red-listed, which means it is a threatened species in Sweden.

The lichens also include several species with a similar distribution, typical of the mild, humid climate of the west coast. The barnacle lichen *Thelotrema lepadinum* and the script lichen *Graphis scripta* are found on the smooth bark of hazel, rowan and alder in wet fens, while *Lecanactis abietina* and *Felipes leucopellaeus* grow on damp, standing spruce trees. Barnacle lichen have fruiting bodies (apothecia) that resemble barnacles, while those of the script lichen look like spidery writing, and those of *Felipes leucopellaeus* resemble cats' paws. See photos on page 12.

Fungi

One typical species of Gårdsjön's damp, nutrient-poor soils is the funnel chanterelle, whose dark brown, well-camouflaged fruiting bodies appear in autumn, from September until the first frost. This fungi is believed to be more common as a result of soil acidification. An important part of the research around Gårdsjön is to study and analyse the changes in plant and animal life due to different influences, such as acidification or liming.

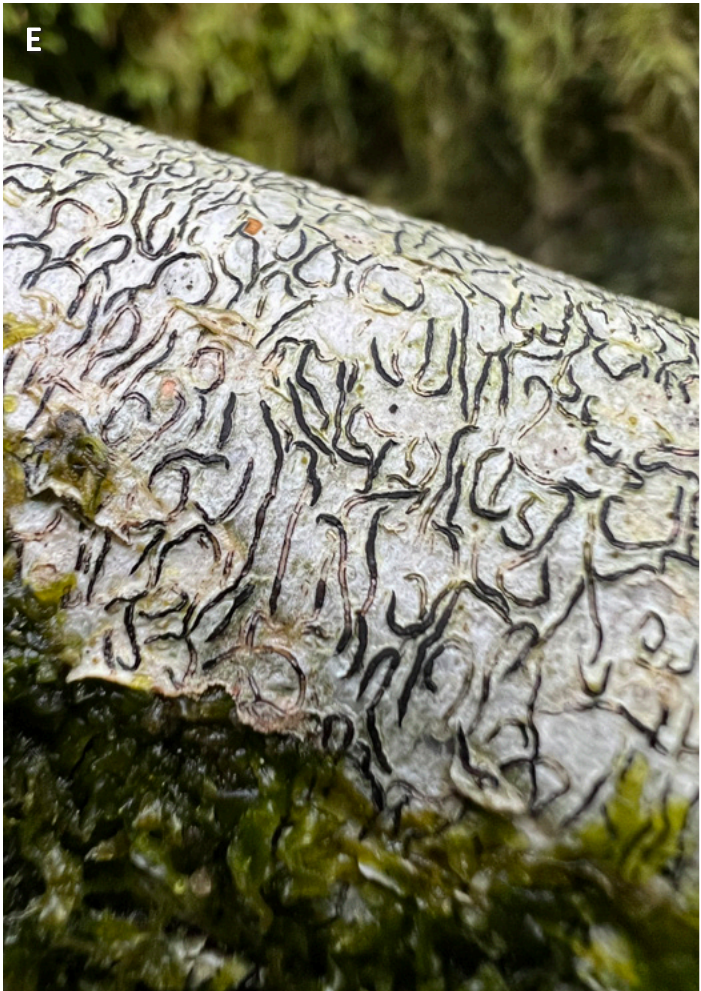
Insect life

Insects are the most species-rich group of organisms, with a total of several million known species in the world and just over 30,000 in Sweden. Around Gårdsjön you are most likely to see midges, flies and dragonflies. But you might also come across a beetle on a forest path, or the beautiful swallowtail butterfly whose larvae live on the flowers of umbellifers such as milk parsley in fens and near lakes. Another insect you can see evidence of is the spruce bark beetle, *Ips typographus*, whose Latin name describes the pattern of larval tunnels that the species makes under the bark of spruce trees. The spindly or sometimes dead spruce trees around Gårdsjön are a result of infestation by spruce bark beetle. This is one of forestry's worst enemies, causing enormous financial loss, especially after hot, dry summers.

Slender St John's wort, *Hypericum pulchrum*, is a red-listed species you can see in a few places around Gårdsjön. It has evergreen leaves and flowers with red anthers

The spruce bark beetle, *Ips typographus*, attacks and kills spruce trees.

Some lichens from around Gårdsjön. Blood lichen *Mycoblastus sanguinarius* (A), old-growth lichen *Lecanactis abietina* (B), *Felipes leucopellaeus* (C), barnacle lichen *Thelotrema lepadinum* (D) and script lichen *Graphis scripta* (E).



Few species but lots of birds

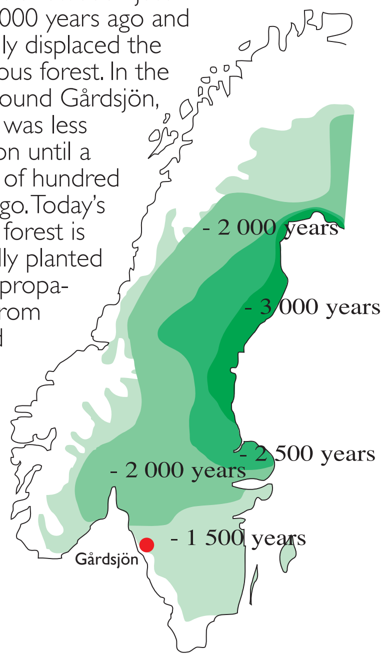
There are many birds around Gårdsjön but they only represent a few species. Around 30 species nest in the land around the lake. The jay is one of the most eye-catching – and noisiest – in summer. The jay plays an important role as it collects and spreads acorns, which can then grow into new oak trees. There are also several birds of prey in the Gårdsjön area, including osprey and several species of owl. In early spring you can hear the whistling of the Eurasian pygmy owl. Despite its small size, it is not to be messed with. If you mimic it too closely it will see you as a competitor and attack, and can tear off your hat in no time at all. From the lake you can sometimes hear the melancholy call of the black-throated loon.

In autumn and winter, various-sized flocks of small birds pass through the forest around Gårdsjön. These feeding flocks include willow tits, crested tits, coal tits, goldcrests, nuthatches and treecreepers. This flocking behaviour increases their chances of survival in winter. The birds scour the crowns of trees for spiders and other suitable food. Different species are known to forage in different parts of the canopy. Each species has its own ecological niche. The smallest – goldcrests and coal tits – visit the tips of the branches. Crested tits explore the middle zone, while willow tits hunt around the roots of branches. The trunk is explored by the tree creeper, which climbs in a spiral from root to crown.

A century ago the landscape was more open

It may surprise you that large parts of Svartedalen were treeless, heavily grazed moorland in the 19th century. Sheep and cattle grazed wide expanses of land. When the heather became thick and woody, the moors were burned. The landscape we see today is the result of conifer planting and prolonged overgrowth of the once open landscape. Several thousand years ago the area was covered with deciduous forest dominated by oak. Spruce, which is the most common species in the landscape today, came to the north-east of Sweden just over 3,000 years ago, and arrived in western and southern Sweden relatively recently. The more drought-resistant, sun-loving pine came from the south long before spruce migrated to Sweden.

Spruce forest attacked by spruce bark beetle.



Spruce began to populate the east of Sweden just over 3,000 years ago and gradually displaced the deciduous forest. In the area around Gårdsjön, spruce was less common until a couple of hundred years ago. Today's spruce forest is generally planted or self-propagated from planted trees.

Rödlistade arter

There are over 50,000 different species of plants, fungi and animals in Sweden. They include 4,746 "red-listed" threatened species (Artdatabanken 2020). Acidification, water pollution, soil drainage and deforestation pose serious threats. Artdatabanken (the Species Information Centre) collects and analyses data on red-listed species. If you see a red-listed species please report it to Artportalen (www.artportalen.se).

Biological group	no. of red-listed species
birds	116
amphibians and reptiles	7
beetles	933
butterflies	549
vascular plants	434
lichens	308
mosses	282
large fungi	851
other groups	1 266
Total:	**4 746**

FACT BOX: Protected species

Around 585 species in Sweden are protected. All orchids, amphibians, reptiles, bats and wild birds are protected in Sweden. A further 43 plant and animal species are protected in some counties.

Protected species at Gårdsjön

All amphibians, reptiles and birds are protected. Aside from birds, the protected species recorded in the area are the moor frog, common frog, common toad, grass snake, slow worm, adder and smooth snake. Protected plants are the foxglove, northern fir moss, heath spotted orchid, greater butterfly orchid and creeping lady's tresses.

Red-listed species

Red-listed species are those that are threatened or at risk of extinction unless they are protected or special measures are taken. The purpose of the red lists is to provide a basis for decisions on various methods of legal protection and other biodiversity measures.

Threats may come from hunting, fishing, pollution, forestry or agriculture. In Sweden, more than 4,700 out of roughly 60,000 known species are red-listed. There are not many red-listed species in the Gårdsjön area, but the shallow, nutrient-poor soil of areas like this rarely supports many red-listed species. Red-listed species found around Gårdsjön include slender St. John's wort, heath rush, black woodpecker and smooth snake.

List is revised every five years

The lists of red-listed species are updated every five years. They are drawn up by specialist committees for Artdatabanken at the Swedish University of Agricultural Sciences. The lists are then verified by the government.

Why is biodiversity so important?

There are many reasons for conserving biodiversity, but most importantly: all organisms have the right to exist, we can learn and benefit from understanding them, and they could provide important genetic resources in the future.

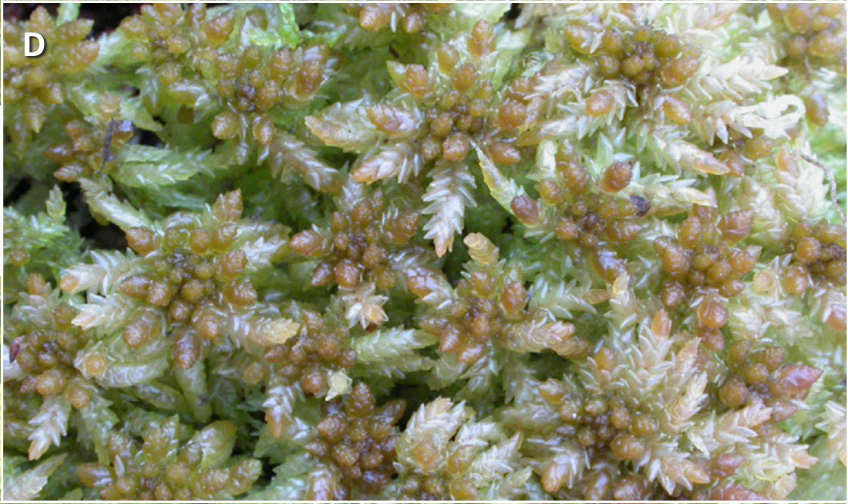
Protected species

Protection is a legal form of conserving species. It's aim is to protect a plant or animal species that is in danger of extinction. It may also be required to meet international obligations.

The method of protection varies a little between species. For plants, protection usually means we must not pick, dig up or otherwise remove or damage protected plants. For animals, it means we must not kill, injure or capture protected animals. The protection of birds also applies to their eggs and nests. The hunting of wildlife is instead covered by hunting legislation. Some species, such as the smooth snake and moor frog, have further protection, which means you must not disturb them or damage their breeding grounds or resting places.

Some protected species around Gårdsjön: Stiff club moss *Lycopodium annotinum* (A), grass snake *Natrix natrix* (B), common toad *Bufo bufo* (C), greater butterfly orchid *Platanthera chlorantha* (D) and smooth snake *Coronella austriaca* (E).


A
B
C
D
E



Typical mosses around Gårdsjön include common haircap moss *Polytrichum commune* (A), little shaggy moss *Rhytidiadelphus loreus* (B), greater fork moss *Dicranum majus* (C), papillose peatmoss *Sphagnum papillosum* (D), greater whipwort *Bazzania trilobata* (E) and greater featherwort *Plagiochila asplenioides* (F).

Lakes in the Svartedalen area

Gårdsjön is a typical "Svartedalen lake".

The type of lake found in an area largely depends on its surroundings. Lakes that are surrounded by sparse coniferous forest and shallow soil are also nutrient-poor and are known as oligotrophic. The lakes in the Svartedalen area are nutrient-poor but their colour ranges from pale brown to dark brown. The brown colour of some lakes is due to substances called tannins. These come from the forests and mires in the lake's catchment area. Tannins break down slowly, so lakes with a very long retention time are often clearer than those with a shorter retention time. One lake in the Svartedalen area that is very clear is Torrgårdsvattnet, which has a visual clarity of 10 to 15 metres. The nutrient-poor lakes of Svartedalen are also sensitive to acidification, and the acidic, sulphur-rich emissions that were released during much of the 20th century overcame the ability of the lakes and surrounding soils to neutralise the acid rain. In most of the lakes, acidification in the 1960s and 1970s was so severe that fish stocks were wiped out. Extensive liming of lakes has been carried out in the area to restore the water chemistry so that fish and other animals and plants can survive and reproduce. Although emissions have

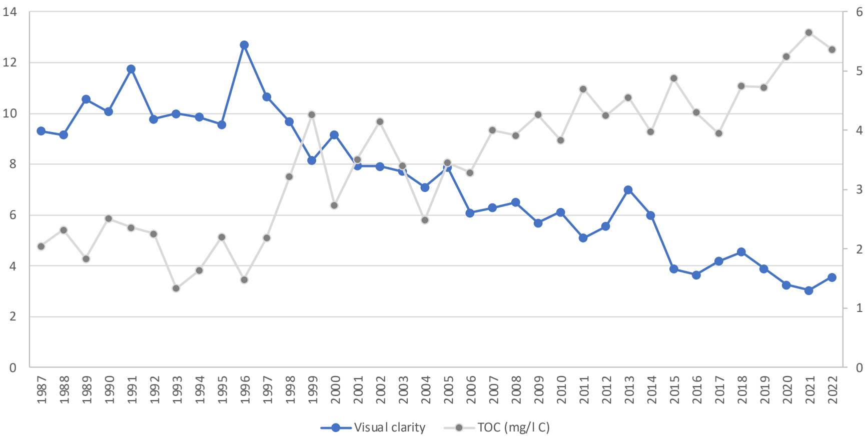
Liming Lake Gårdsjön from a boat (right).

Lake Torrgårdsvattnet (below) – a very clear and nutrient-poor lake in the Svartedalen area.

thankfully been reduced, the effects of acidification are still apparent, as recovery through natural weathering processes is slow in such nutrient-poor environments. This means it is still necessary to lime most of the lakes in the area to prevent re-acidification.

Browner lakes and waterways

Many lakes in Sweden have become browner in recent years, including the lakes in the Svartedalen area. In Lake Härsvatten, levels of total organic carbon (TOC) have risen from around 2 mg/l in the 1990s to 4–5 mg/l today. The visual clarity has decreased as a result (see figure). Extensive research into the cause of this widespread trend points to several contributing factors. Climate changes in recent decades have meant shorter and wetter winters and longer growing seasons, so more organic matter is carried into lakes. Intensive forestry, including the drainage of forest land, also means that organic matter is carried more quickly into lakes and rivers. Another change that results in browner water is actually reduced acidification. One explanation may be that soil recovery has led to higher levels of dissolved organic carbon (DOC). The more acidic the water in the soil, the lower the level of DOC. At the peak of acidification, our lakes were unnaturally clear.



Total Organic Carbon (TOC, the right y-axis) has steadily increased while the visual clarity (the left y-axis) has decreased in Lake Härsvatten, a reference lake in the Svartedalen area.

Acidification

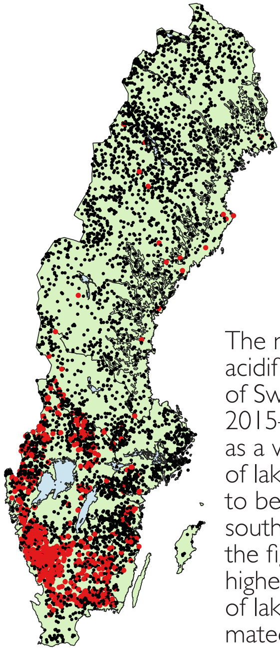
Acidification killed off the fish in many lakes as far back as the 1960s and 1970s. Roach are one of the more vulnerable species and start to suffer reproductive problems when the pH level drops to 6, while perch start having problems when the pH falls below 5.5.

Signs that fish stocks are affected by acidification can usually be seen in the age distribution, as younger fish start to disappear. In waterways, trout are tolerant down to pH 5.6, while salmon and freshwater pearl mussels may be affected at a pH just above 6.0. Low pH values can also be toxic to fish and inhibit the hatching of eggs. Low pH values may not be the main cause, but in combination with increased leaching of aluminium, which also forms toxic compounds, it usually poses the biggest problem for fish. In lakes with completely depleted fish stocks there are major changes in the entire ecosystem that also benefit some species. These often include species that are eaten by fish, such as diving beetles and some species of dragonflies.

Another example are phantom midges. The larvae of one Swedish species, *Chaoborus flavicans*, have a behaviour that allows them to avoid fish predation, while another Swedish species, *C. obscuripes*, lacks this behaviour and is therefore absent from lakes stocked with fish. Paleolimnological studies (the study of animal or plant remains in lake sediments) have shown that the mandibles of the latter species occur in the shallowest sediment layers of lakes Gaffeln and Lilla Hästevatten, but are completely absent from deeper sediment. This is clear evidence that the lakes had a fish population but that this was eliminated, allowing *C. obscuripes* to invade.

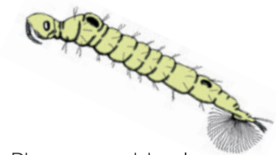
Will the situation improve?

Gårdsjön is currently limed and therefore has little value as a reference lake, but the nearby Härsvatten has never been limed, so it provides valuable chronological records of water chemistry, bottom fauna and plankton since the late 80s. Here, as in several other acidic reference lakes, it can clearly be seen that international efforts to reduce acidifying emissions have had positive effects. Sulphate levels are falling, pH and alkalinity are rising, and although fish have not yet returned, positive effects can be seen in the fauna, such as an increase in the number of phytoplankton species.



The map shows the acidification status of Swedish lakes in 2015–2020. In Sweden as a whole, around 7% of lakes were estimated to be acidified, but in south-western Sweden the figure was much higher – around a third of lakes were still estimated to be acidified.

Perch
Perca fluviatilis

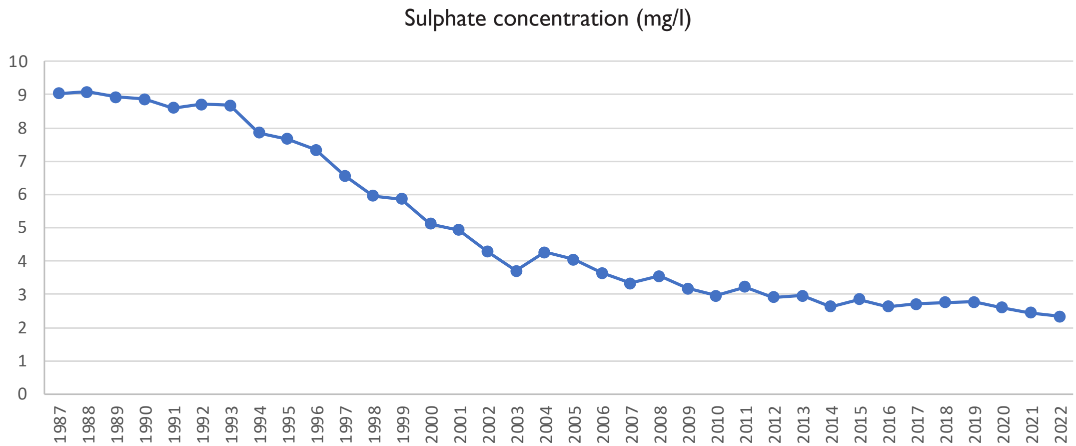


Phantom midge larva
Chaoborus sp.

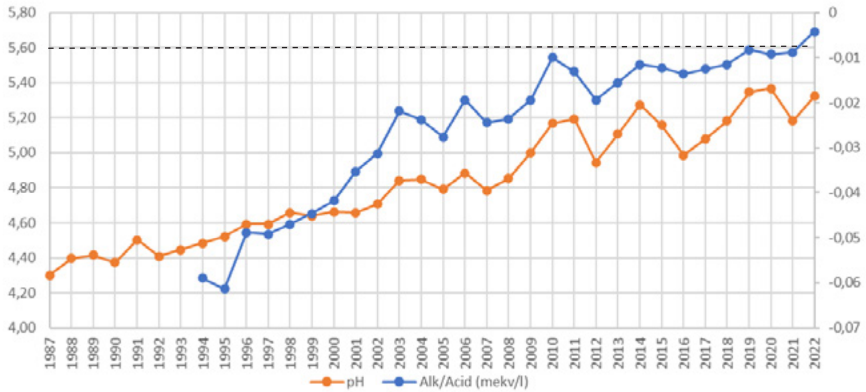
Water boatman
Glaenocorisa propinqua

Lake Härsvatten, a reference lake in the Svartedalen nature reserve.

The graph on the right shows the falling sulphate levels in Lake Härsvatten.

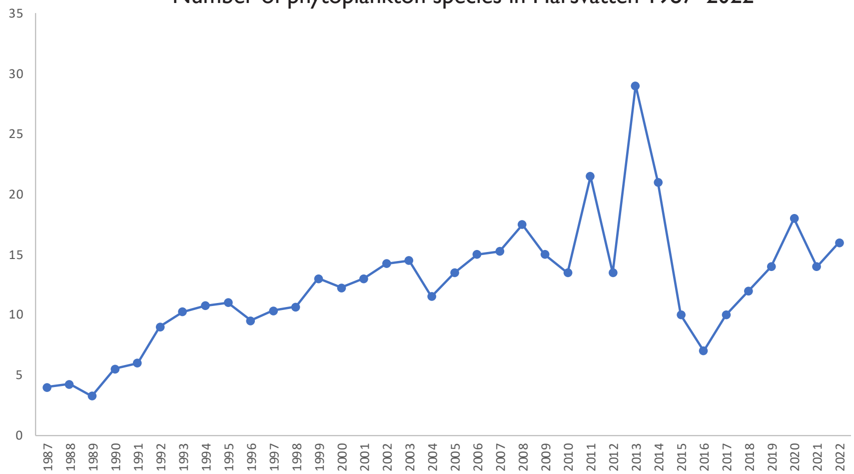


pH and alkalinity in Härsvatten 1987–2022



The graph above shows how alkalinity (buffering capacity, right y-axis) and pH (left y-axis) have recovered in Lake Härsvatten although it has never been limed. The dotted line, pH 5.6, is the pre-industrial reference value obtained from the Magic model.

Number of phytoplankton species in Härsvatten 1987–2022



The number of phytoplankton species in Lake Härsvatten has risen significantly since the late 1980s, but is still low compared to lakes unaffected by acidification.

FACT BOX: The Water Framework Directive

In 2000, the EU established regulations for treating water, known as the Water Framework Directive (WFD). The WFD was incorporated into Swedish legislation in 2004 through the Water Administration Regulation. Work follows 6-year cycles and its aim is that all water bodies have a healthy chemical and ecological status and should not deteriorate. Exceptions are only allowed if socially beneficial activities such as hydropower generation affect the physical environment, and this societal need cannot be met in another way that is better for the environment.

Sweden has now entered its fourth six-year cycle, but there is still a long way to go before we reach the targets. Eutrophication, acidification and environmental toxins make it difficult to meet targets.

Another issue that may not have gained as much attention as environmental issues until the WFD came into effect is the physical impact we have on rivers and lakes. Obstacles such as dams and poorly designed road culverts affect the ability of fish to migrate, for example. The hydrology of many waters is affected by regulations, straightening and drainage.

Lastly, we have altered the land morphology in many ways, such as building and farming too close to waterways. Until the 1970s, timber was also rafted along watercourses, many of which were cleared of all the obstacles that otherwise help to create diverse, species-rich environments.

Gårdsjöstugan (A). Sampling container for acidifying substances (B). Toad spawn from Gårdsjön. Toads are poisonous and are not eaten by fish, unlike frogs. There are plenty of toads but fewer frogs in Lake Gårdsjön (C). View from Gårdsjöstugan conference room (D).

Nitrogen in the forest

Nitrogen – too much of a good thing?

Deposition of nitrogen compounds from the air onto the Earth's surface affects ecosystems in various ways. Nitrogen deposition is partly a natural process. The problem is that various human activities increase airborne emissions of nitrogen, and hence deposition, to levels that are several times higher than natural. Nitrogen is an essential nutrient for plant growth. Higher deposition of nitrogen compounds often leads to increased plant yields. In a managed forest, increased nitrogen deposition can increase timber yield. Nitrogen deposition on agricultural land can also improve crop yields and increase fertiliser efficiency. Soils are an important carbon sink, storing large amounts of organic carbon, and nitrogen deposition can have a positive effect on carbon sequestration not only in plants but also in soils. Carbon sequestration is the process of capturing and storing CO_2 from the atmosphere, which helps to reduce the amount of CO_2 in the air and hence mitigate its climate impact.

But nitrogen deposition also has a number of negative effects and affects the entire landscape, not just the areas where it is beneficial. Increased nitrogen deposition on land can cause eutrophication of water bodies as nitrogen begins to leach into them, leading to harmful algal blooms and reduced water quality. It can also acidify soil and reduce soil fertility by leaching out base cations such as calcium and potassium. Heavy and persistent deposition can also inhibit plant growth. Increased nitrogen can alter the balance between various soil microorganisms, affecting the production and uptake of methane and generating more nitrous oxide, two potent greenhouse gases that contribute to global climate change.

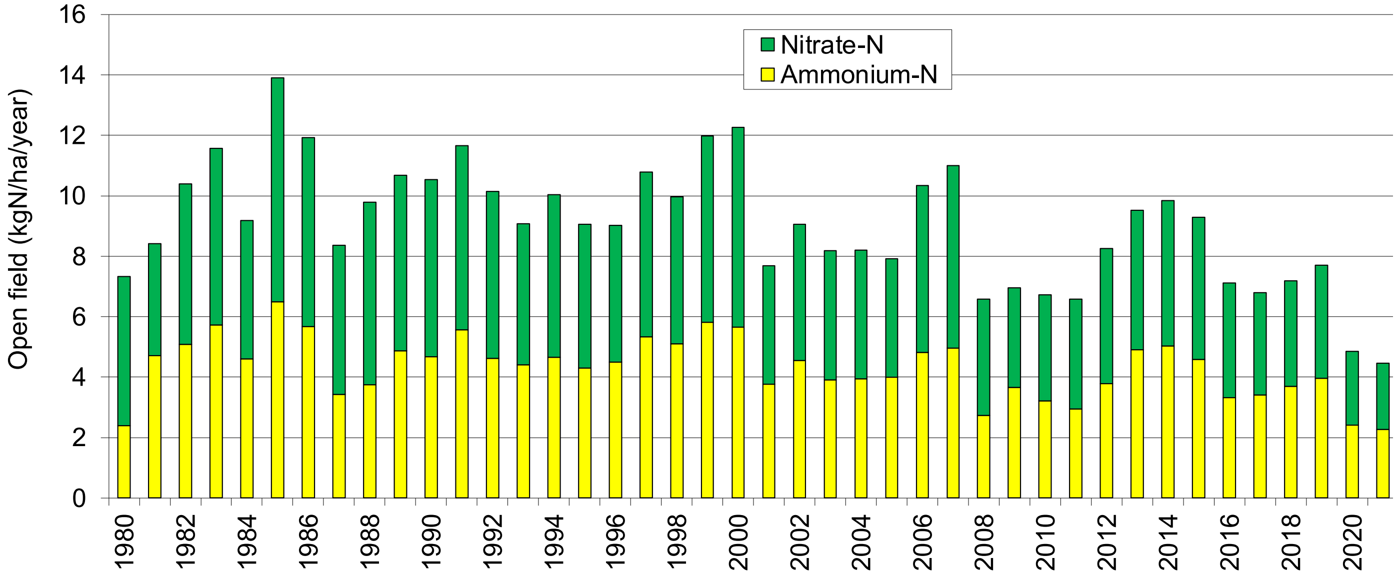
High nitrogen deposition can also cause biodiversity loss by eliminating many plant species that are nitrogen-sensitive, as well as other nitrogen-sensitive organisms such as lichens and mosses. It can thus alter the balance of ecosystems and reduce biodiversity. High levels of nitrogen oxides in the atmosphere contribute to the formation of ozone, which is harmful to vegetation and humans. On the subject of human health, higher levels of reactive nitrogen – in oxidised or reduced form – favour the formation of particulates, which have a further impact on human health. This makes it vital to work systematically to prevent negative impacts on the environment, climate and human health by reducing emissions of nitrogen into the air and water.

Road traffic emits nitrogen oxides (NOx) and agriculture emits ammonia (NH_3).

To sum up, all life needs nitrogen, but in the natural state biologically available nitrogen is a scarce resource that limits growth. Emissions of nitrogen into the air lead to increased atmospheric deposition that often stimulates growth, but increased growth is rarely desirable in natural, low-productivity ecosystems, and higher deposition also has several other consequences.

Nitrogen deposition trends over time

Nitrogen deposition is slowly decreasing in Sweden and the rest of Europe, but it is still at elevated levels and will not fall to background levels in the foreseeable future. Determining precise historical levels of natural nitrogen deposition is difficult, but large parts of central and northern Sweden that are far from large emission sources usually have annual deposition rates of around 2 kg per hectare.



Deposition of nitrogen in open field at Gårdsjön, measured as nitrate (NO_3) and ammonium (NH_4).

Sweden is not as badly affected by elevated nitrogen deposition as several other European countries with higher population densities, more intensive agriculture, and more transport and industry. But this applies mainly to northern and partly to central Sweden, where atmospheric deposition of nitrogen is low. Southern and south-western Sweden are affected more as they are closer to emission sources in Sweden and abroad.

The largest emissions of nitrogen in Sweden come from agriculture, which together with combustion accounts for more than 80 percent of total domestic airborne nitrogen emissions. However, the biggest source of deposition in

Sweden is the long-range transport of nitrogen from sources outside Sweden. Some Swedish emissions are likewise carried by winds beyond our borders and cause problems in neighbouring countries. Showing the negative effects of nitrogen deposition in Sweden and abroad provides a strong argument in international efforts to reduce overall emissions.

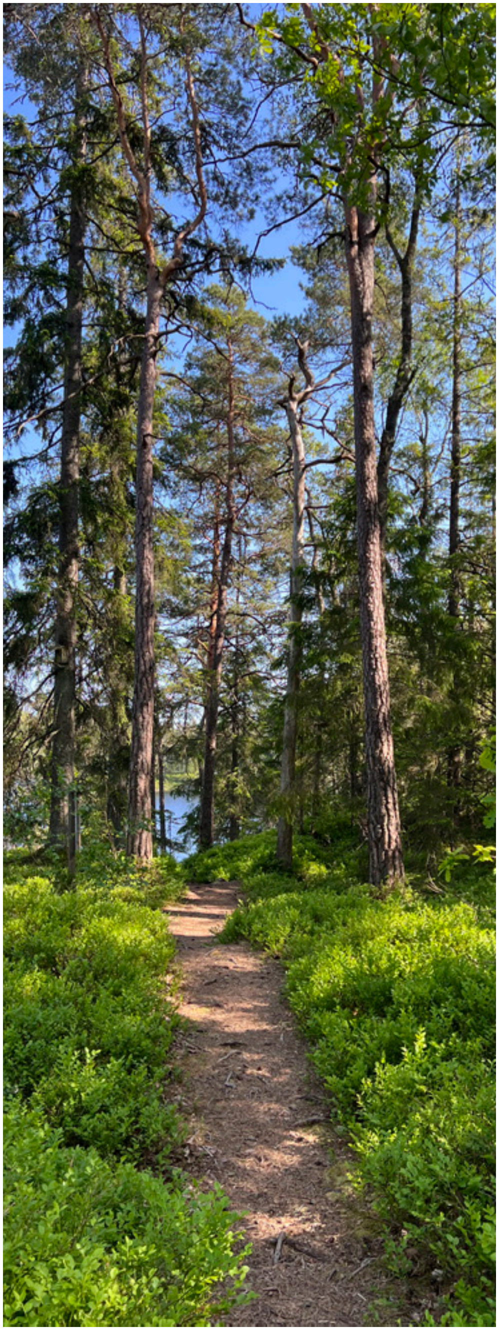
Research on nitrogen at Gårdsjön

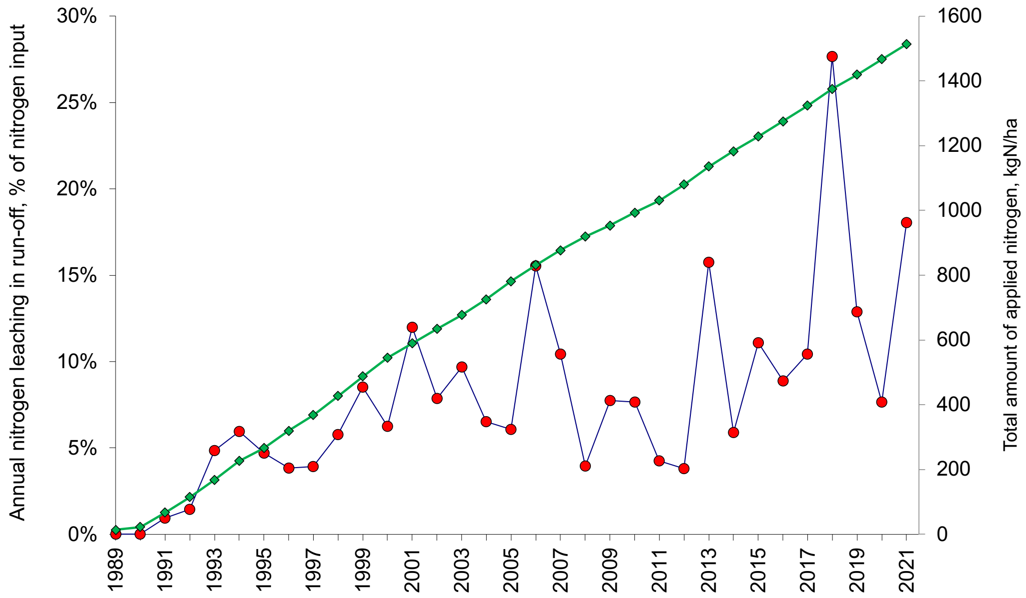
The effects of nitrogen deposition in natural forest ecosystems have been examined at Gårdsjön using a nitrogen fertilisation study. This study tries to answer the following questions: Can we predict when a system becomes nitrogen-saturated? Can fertilisation studies simulate the effects of elevated atmospheric deposition? Is there a relationship between nitrogen application and nitrogen leaching? Does leaching lead to acidification? Does a high nitrogen input lead to toxic effects in trees and does it affect natural plant communities?

Annual fertilisation with 40 kg nitrogen per hectare in catchment G2 at Gårdsjön was started in 1991 as part of the EU-funded NITREX project (NITRogen saturation EXperiment). Measurements in the area started two years before treatment began. After the NITREX project ended in 1995, treatment continued under various national and international projects and has also been supported for a long time by the Swedish Environmental Protection Agency (EPA). This means the catchment area has been treated with nitrogen once or twice a month continually since 1991, i.e. for over 32 years at the time of writing.

If a natural ecosystem is exposed to a persistently high nitrogen load it is believed that it will eventually transition from a nitrogen-limited system to a nitrogen-saturated system, with a risk of nitrogen leaching and changes in species composition. However, there are few documented cases where such a system change has been demonstrated. The area around Gårdsjön is relatively low in nitrogen. The humus in the forest soil has a high carbon/nitrogen (C/N) ratio of about 35 (by weight). Before fertilisation began, there was no NO_3-nitrogen in the run-off from the area. The high C/N ratio and little or no nitrate content in the run-off (or groundwater) are good indicators that the catchment area is not eutrophied. This made the G2 area at Gårdsjön an ideal candidate for experimentally studying the transition to a nitrogen-saturated system by adding nitrogen.

In the first five years after fertilisation began, the nitrogen content of the stream increased in proportion with the total nitrogen input from fertilisation. At the beginning of the NITREX project it was expected that more and more nitrogen would leave the forest area in run-off as nitrogen was added, but this has not been the case. Instead, leaching remained between 5 and 10 percent of the annual nitrogen input for a long time.





Nitrogen leaching from the Gårdsjön NITREX site as % of annual nitrogen input (nitrogen deposition + addition), and the total amount of nitrogen applied (green line, right y-axis).

Extreme weather conditions, felling or insect infestation can all affect the leaching of nitrogen from a forest site. Looking at the graph, data collected in 2018 from the NITREX site shows an exceptionally high level of nitrogen leaching, probably due to the extremely dry summer that year, which was followed by extensive spruce bark beetle infestation in the NITREX area and forests around Gårdsjön. This weather event did not cause the ecosystem to continue leaching out large amounts of inorganic nitrogen, as shown by the decrease in leaching from 28% after the drought to 13% the following year and 8% in the year after that. It is however likely that adding nitrogen to the forest reduced its capacity to cope with disturbances without leaching nitrogen. The neighbouring control area, F1, which was not treated with nitrogen but also contains spruce forest that was attacked by spruce bark beetle in 2018 in a similar way to the NITREX area, continues to show little or no leaching of inorganic nitrogen, despite weather variations and severe attack by spruce bark beetle.

Nitrogen input has not only affected nitrate leaching. Other effects include rises in the nitrogen content of needles and in nitrous oxide emissions from wet areas of soil. The composition of fungal communities in the soil that are vital for nutrient uptake by trees has shifted towards species that thrive in high-nitrogen environments. The soil bacterial community also shifted from species that mainly thrive in nutrient-poor conditions to those that prefer nutrient-rich environments. There is thus evidence that many aspects of the forest ecosystem, such as run-off, groundwater and soil water chemistry, nitrogen levels in needles, the composition and functionality of soil microbial organisms, have also been affected by the large increase in nitrogen input.

But we cannot conclude that the high nitrogen load that the NITREX area has been exposed to has led to the disastrous consequences that too much nitrogen can cause in other locations, as seen in the Netherlands and parts of Germany. One likely reason why the nitrogen added to the NITREX area has mostly been taken up by the forest ecosystem is that, although the addition was large compared to annual atmospheric deposition, it is still small compared with the existing nitrogen content of the soil and forest. In addition, the soil was extremely low in nitrogen to begin with, and the nitrogen was applied in many small doses, so microorganisms and vegetation have had time to adapt. Fortunately, it takes a lot of nitrogen and a lot of time to saturate a severely nitrogen-limited system to the point where microbes, trees and other vegetation cannot take up any more nitrogen. The NITREX project at Gårdsjön shows the value of long-term studies. One surprise was the slow rise in the nitrate level in run-off, which contradicted the hypothesis that such a high nitrogen load would cause nitrogen leaching to increase rapidly. It is expected that continued nitrogen treatment will bring us even closer to answering questions about nitrogen and carbon turnover in the forest and the long-term effects of elevated nitrogen deposition.

Excess nitrogen deposition can cause biodiversity loss.

The water of Lake Gårdsjön is crystal clear due to nutrient deficiency (lack of nitrogen and phosphorus) and brown due to humic substances from the surrounding conifer forest.

Monitoring the environment

The Gårdsjön IM site monitors many parameters, including the amount of water flowing out of the catchment area.

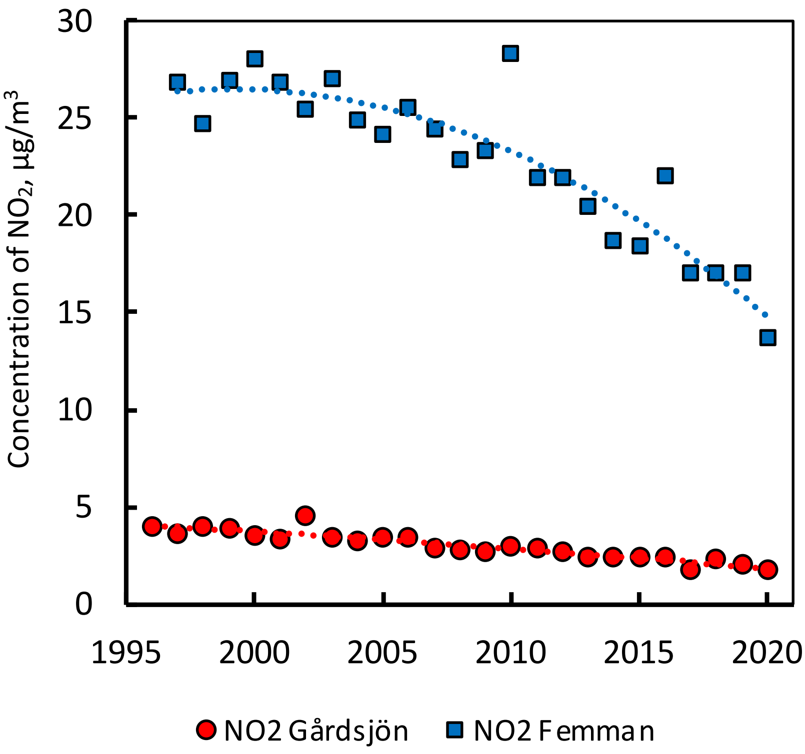
There are various ways of studying how the environment is affected by pollution, land use and climate. One is to conduct laboratory experiments in which different parts of the ecosystem or its organisms are subjected to controlled treatments, such as adding fertilising nitrogen, acidifying substances or exposure to a toxic gas such as ground-level ozone.

Another important method for understanding the state of the environment is to carefully study trends in air pollution levels, water pH, numbers of certain plants and animals, and climate factors such as temperature and humidity over a long period of time. This is called environmental monitoring. One vital element of environmental monitoring, in addition to being long-term, is to continue using the same established methods so that results can be compared over time and any trends or changes observed are not due to a new measurement method.

At Gårdsjön it is particularly important that there is a dedicated sampling area for integrated environmental monitoring (IM), where a variety of methods are combined to monitor the development of a forest ecosystem. This is one of four similar sites in Sweden that are part of a European network which follows the same approach and coordinates activities internationally. Integrated environmental monitoring at Gårdsjön began in 1991.

Air quality monitoring

Air quality is monitored nationally and locally to determine whether concentrations reach harmful levels or guideline values for health and ecosystems, and to test whether emission mitigation measures are yielding results. In large cities, a high density of emission sources, particularly road traffic, contributes to higher levels of air pollutants such as particulate matter and nitrogen oxides. These can have serious effects on human health and affect other organisms. Local air pollution is strongly influenced by how effectively the air is mixed. When there is no wind, concentrations are much higher than when it is windy, so pollutant levels vary greatly with weather conditions.

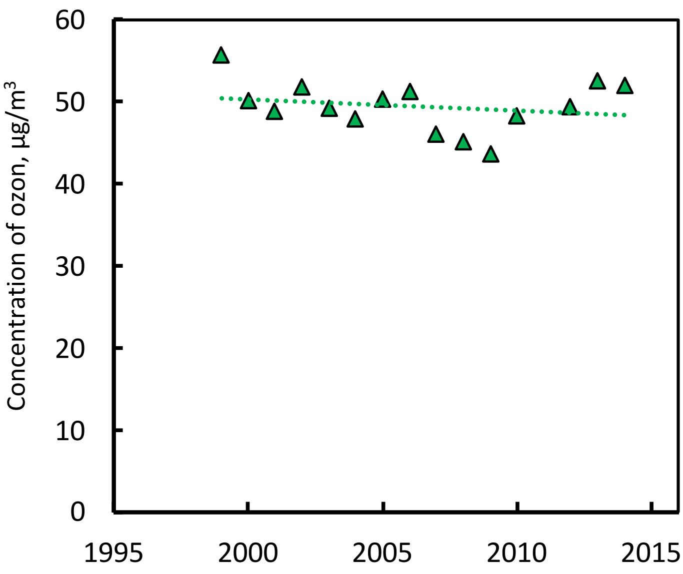


Above. Passive samplers for gaseous pollutants such as NO_2 and O_3 are attached to the underside of a rain shield. They are usually exposed for periods ranging from one week to one month and then analysed in the laboratory to determine the average concentration over the exposure period

Left. Concentrations of NO_2 over the period 1996–2020 at Gårdsjön and on the roof of the Femman building in central Gothenburg.

Nitrogen dioxide, NO_2, is one of the main air pollutants and is created in various combustion processes by the reaction of oxygen and nitrogen from the air when they are heated. NO_2 contributes to a number of environmental problems. It can be converted into nitric acid and then contributes to acidification and eutrophication. The formation of ground-level ozone also depends on NO_2 levels. NO_2 itself is also toxic to humans and plants.

The level of NO_2 has been monitored at Gårdsjön since 1996 using passive samplers – small "buttons" that absorb the pollutant and can then be analysed in a laboratory. NO_2 levels are often quite high in dense urban areas, mainly due to emissions from vehicles with internal combustion engines. The graph on the previous page shows how NO_2 levels varied over the period 1996–2020, at Gårdsjön and on the roof of the Femman building in central Gothenburg, which monitors air pollution levels in urban background air. Two things are clear from the graph. First, levels in Gothenburg are considerably higher than at Gårdsjön, reflecting the much higher level of emissions in the city. It should also be noted that the concentrations at street level in Gothenburg can be much higher than on the roof of the Femman building, 30 metres above the surrounding traffic. We also see that concentrations have decreased significantly. They have almost halved in the 25 years since measurements began. The improvement is due to several factors, but the use of electric cars and emission control systems on many vehicles has played a large part in reducing NO_2 emissions.



Historical trend in atmospheric ozone levels at Gårdsjön.

Ground-level ozone has also been monitored using passive samplers at Gårdsjön, but not for the same length of time as NO_2. As the graph on this page shows, ozone levels have remained relatively steady. No significant improvement has been seen here or at other sites. Ozone is formed by the action of sunlight on atmospheric pollutants such as nitrogen oxides and volatile organic compounds. These processes take time and ozone formation therefore occurs across large geographical areas.

Environmental monitoring of water

Several organisations are involved in monitoring freshwater in Sweden. Studies on lakes and flowing water are carried out for various purposes. Here are three key questions that environmental monitoring seeks to answer:

To understand how the environment in lakes and flowing water develops, it is important to regularly study the water's chemical composition and the organisms present.

1. What long-term changes occur in lakes that are relatively unaffected by local emissions?

National monitoring is largely carried out in lakes and rivers that are unaffected by local emissions from sewage and industry and have little impact from agriculture. Lake Härsvatten is close to Gårdsjön and has been closely monitored as a reference lake since the mid-1980s, as mentioned earlier. This lake and other "trend lakes" across Sweden are monitored for water chemistry, phytoplankton, bottom fauna and fish stocks. National monitoring also includes a programme of "cyclically monitored lakes". This includes a large number of polluted and unpolluted lakes that are only sampled every sixth year. The programme covers large areas and permits observation of large-scale changes, but is not designed to monitor trends in individual lakes.

2. How does liming affect lakes and rivers?

The county administrative boards also carry out important environmental monitoring. They have a regional environmental monitoring programme (REM), but also carry out monitoring to assess the liming measures taken to counter acidification, to ensure they have the desired results. Lime effect monitoring (LEM) is intended to assess these effects. Many lakes and waterways in western Sweden have been or still are acidified unless they have been limed. LEM is very extensive in Västra Götaland County. LEM monitors water chemistry, in particular to determine the lowest pH value during the year. It is also important to monitor the biology of limed waters, which includes sampling bottom fauna and fish

3. How are lakes and watercourses affected by discharges from treatment plants and industry?

Another important element of Swedish water monitoring is the studies carried out by water conservation associations or water councils, known as coordinated recipient monitoring (CRM). The purpose of this monitoring is see what impact local discharges have on water quality. Water conservation associations and councils are usually made up of municipalities and companies that have a legal obligation to monitor the impact of their activities. To do this effectively, they collaborate in a CRM programme.

Electrofishing is a method for assessing fish stocks in waterways. Electrofishing has been used in the river Anråse in Tanum municipality to measure and record fish. The photo shows a young salmon (smolt) that is ready to emigrate.

Living organisms as environmental indicators

The section on freshwater above mentioned that in some cases living organisms such as plankton and fish are monitored. Biological environmental indicators are also studied on land. This can involve studying the numbers of species with different sensitivities to environmental impacts. Another method is to examine whether native species or species that are cultivated as bioindicators show specific symptoms that can be linked to pollution. Organisms such as selected plants that take up large amounts of metals or other pollutants and can be analysed for such pollutants are known as bioaccumulators.

In the case of ground-level ozone, a certain type of tobacco is a widely used bioindicator. Even at moderately elevated ozone levels, it develops characteristic pale (chlorotic) spots that turn brown over time. The particular sensitivity of this tobacco variety was discovered when ozone levels rose in the south-eastern US around 1950. The photo on the right shows a tobacco leaf from a plant grown in ambient air next to one from a plant grown in filtered air at the same location.

One variety of tobacco has been widely used as an indicator of ground-level ozone pollution in the air. The leaf on the left has been exposed to outdoor air while the one on the right grew in filtered air.

Lichens are a group of organisms that are often overlooked. As mentioned earlier, they are actually fungi that live in symbiosis with algae and/or cyanobacteria that carry out photosynthesis. In many ways, lichens are very

The elegant lungwort *Lobaria pumonaria* is very sensitive to air pollution. In the past it was thought it could cure lung ailments because its surface resembles the alveoli of the lungs.

Lichens are virtually absent from areas with high levels of air pollution, while green algae colonise the tree trunks.

Where the air is clean, lichen flora is more diverse.

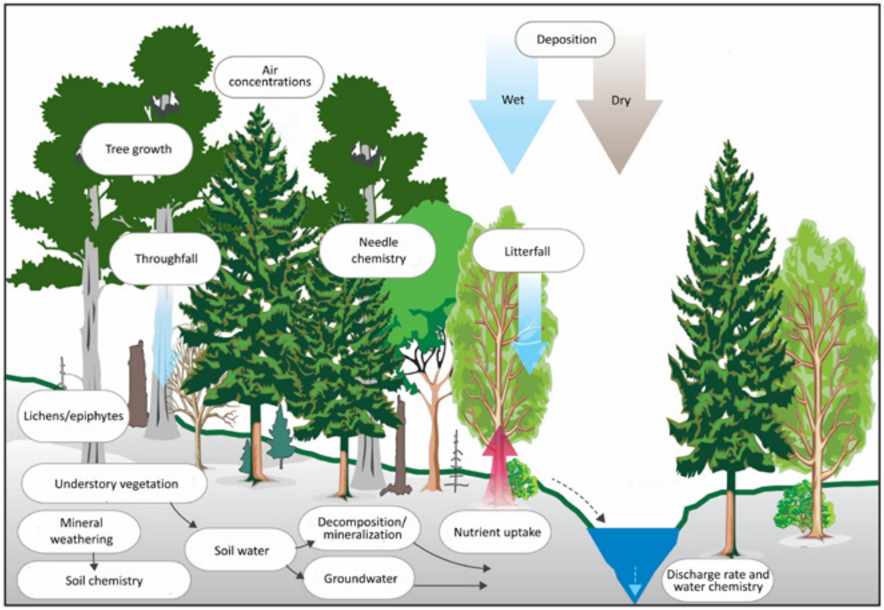
resistant to conditions such as drought, cold, heat and lack of nutrients. This enables them to grow on rocks, tree trunks and soils with low humidity. Unlike plants, which have specific mechanisms to control nutrient uptake, lichens absorb nutrients indiscriminately over their surface area. As a result they also absorb toxic substances – you could say they have little protection from their environment. This means they are relatively sensitive to air pollution, which they also absorb. As early as the late 1800s it was noticed that lichens were starting to disappear from urban areas and industrial areas where pollution levels were high. Because of this they have been widely used as bioindicators.

Sensitivity to pollution varies between lichen species. Some are resistant to air pollution, while others are very sensitive. They may also react differently to different pollutants. For much of the 20th century the pollutant most responsible for the severe loss of tree trunk lichens from all major cities was sulphur dioxide. Now that levels of this pollutant have been greatly reduced, many lichens have returned to the trees in city centres. Having been covered by a thin layer of hardy crustose lichens and algae, they have now been recolonised by foliose and fruticose lichens. But lichens are not just sensitive to sulphur. Nitrogen dioxide also affects them. For some lichens, this gas has similarly harmful effects as sulphur dioxide, but because nitrogen is also an important nutrient, some lichens benefit from it and actually grow better. Beard lichens, horsehair lichens and lungwort lichens are very sensitive to air pollution. Finding them indicates good air quality and there are signs they are also recovering from the effects of sulphur pollution.

The presence of lichens is monitored at Gårdsjön. They show no major changes in recent decades, which can be interpreted as showing that the air quality in this area is not changing much.

More about integrated environmental monitoring at Gårdsjön

Catchment F1 at Gårdsjön is one of four Swedish sites in the Integrated Monitoring (IM) programme. It was launched in Sweden in 1995 as an extension of

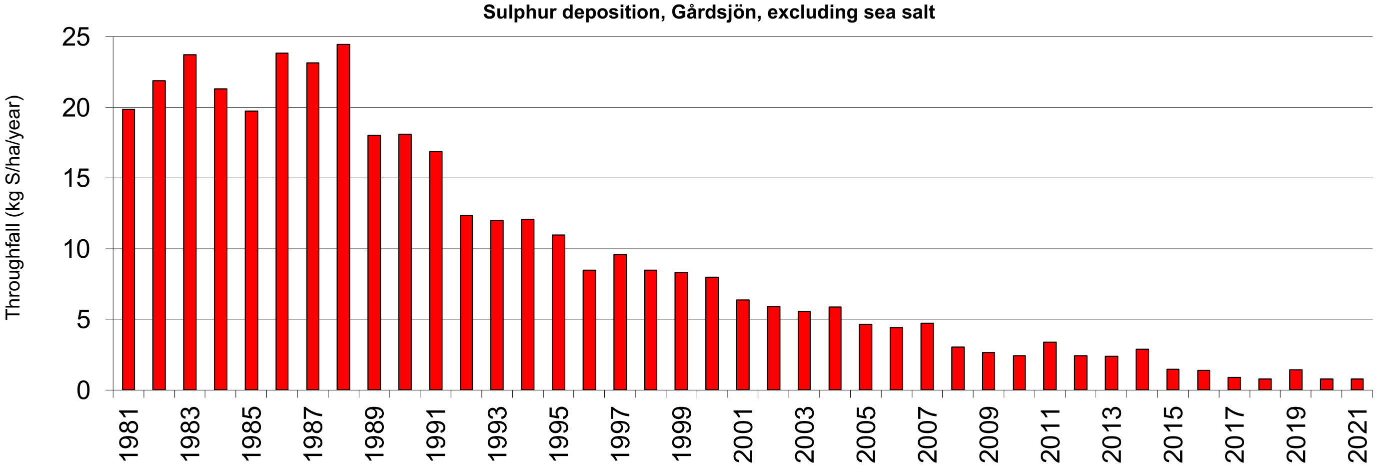


Integrated environmental monitoring looks at several different aspects of the ecosystem. They include biological factors, such as tree growth and the presence of various plants, as well as chemical factors such as air pollutant deposition, pH and the concentrations of substances in soil and water. Hydrological processes are also monitored, such as water flow through the site.

the Swedish EPA's national Programme for Monitoring Environmental Quality (PMK). The four Swedish IM sites were chosen to cover different geographical, depositional and climatic conditions across the country, from the heart of the southern Swedish uplands, via the west coast (F1 Gårdsjön), to a site in Bergslagen and another in central Norrland. These are all catchments in forest ecosystems that are not used for forestry. The Swedish IM sites are financed by the Swedish EPA, but are part of a larger European network comprising over 50 IM stations in 17 countries.

The programme's aim is to monitor and investigate ecosystem effects caused by deposition of long-range air pollutants, mainly nitrogen, sulphur and heavy metals, and it is linked to the UN Air Convention and the EU National Emissions Ceilings Directive.

Because the measurements are used to distinguish between the effects of human impact and natural variations in ecosystems, it is also necessary to monitor physical and chemical processes in soil and water and their effects on living flora over the long term. At the F1 site in Gårdsjön we measure and analyse water flow and water chemistry in the stream, throughfall and precipitation, the chemistry of soil water and groundwater, litterfall and litter decomposition, algae cover on needles, forest growth, ground vegetation and soil chemistry, as well as measuring various climate parameters such as temperatures of air, water and soil, rainfall, wind speed, insolation, etc.



Measurements at Gårdsjön show that sulphur deposition has fallen steadily and very sharply since the 1980s as a result of reducing emissions in Europe. Because Gårdsjön is close to the west coast, sulphate is also added to ecosystem by the deposition of salt particles. This is not an acidifying pollutant and has been excluded.

The collected data are reported annually to the IM programme centre and compiled in annual reports (https://www.slu.se/institutioner/vatten-miljo/miljoanalys/integrerad-monitoring-im/im-publikationer/) and then become publicly available. Data from the IM programmes are used to assess the current state of the environment, effects of environmental improvement measures, and produce forecasts of impact and recovery from air pollution. The data are also used for developing and evaluating models. In this respect, the big advantage is the wide scope of data collected (deposition, air concentrations, water, soil, vegetation, climate) over a long period of time at one site. These time series are not only useful for assessing the effects of air pollution, but also the long-term effects of climate change.

Air pollution and acidification – 50 years of transboundary air quality policy

We take it for granted today that air pollution is an international concern, but this was not the case in the late 1960s when Sweden and Norway called on countries emitting the highest levels of sulphur to take responsibility for their emissions.

Illustration: Klaus Albrechtsen.

1. The Air Convention

In the 1970s, thousands of lakes and rivers in Sweden and Norway were found to be seriously affected by acidification. Thanks to in-depth research and determined political negotiation by the Swedish and Norwegian governments, a new international environmental agreement was reached in 1979. It was named the Convention on Long-Range Transboundary Air Pollution, but is now simply known as the Air Convention.

Almost all European countries, as well as Canada and the US, are now parties to the Air Convention, and it has gradually been supplemented with more detailed protocols setting commitments and requirements for reducing emissions.

Acidification and fish deaths followed by forest dieback

In the early 1980s there were reports of increasing damage to forests, first in former West Germany, followed by a string of other countries. "Forest dieback" became a familiar term, and was linked to high emissions of air pollutants. The lengthening list of countries that were being seriously affected by air pollution led to growing political pressure to reduce emissions. The main focus was on emissions of sulphur and nitrogen oxides from coal-fired power plants and cars.

A better understanding of the harmful effects of air pollution on nature made a big contribution to the first Air Convention protocol in 1985. The 21 countries that signed the protocol pledged to reduce their sulphur emissions by at least 30 percent between 1980 and 1993. This was followed by a protocol for nitrogen oxides in 1988 and another for volatile organic compounds in 1991.

In central Europe, particularly in mountainous areas, there was widespread forest damage and in some cases complete forest dieback in the second half of the 20th century. Photo from the Czech Republic.

> **FACT BOX: Key air pollutants that harm the environment and health**
>
> ***Sulphur dioxide:*** The main human source of sulphur dioxide (SO_2) emissions is the burning of sulphur-containing fuels such as coal and oil, as well as some industrial processes. SO_2 reacts in the atmosphere and can form sulphuric acid, which acidifies the soil and water. SO_2 can also react with ammonium to form ammonium sulphate, which increases levels of $PM_{2.5}$.
>
> ***Nitrogen oxides*** (NOx) is the collective name for nitrogen oxide (NO) and nitrogen dioxide (NO_2), formed when oxygen and nitrogen in the air react at high temperatures, i.e. during combustion. Car traffic is the main source in most urban areas, but energy generation, contracting machinery and shipping also contribute. In combination with organic compounds and sunlight, NOx contributes to the formation of ground-level ozone. NOx can also react with ammonium to form ammonium nitrate, which increases levels of $PM_{2.5}$. Deposition of the nitrogen pollutants NOx and ammonia contributes to acidification and eutrophication of soil and water.
>
> ***Ammonia:*** Emissions of ammonia (NH_3) into the air come mainly from handling and spreading livestock manure and using mineral fertilisers in farming. Ammonia contributes to acidification, eutrophication and elevated levels of harmful particles.
>
> ***Volatile organic compounds*** (VOC) is the collective name for pollutants that form ground-level ozone in the presence of sunlight and nitrogen oxides, and NMVOCs is an abbreviation for non-methane volatile organic compounds. VOCs can be formed during incomplete combus-
>
> continued on next page

In the 1980s, scientists collaborating under the Air Convention succeeded in developing ecologically based critical loads for various natural environments and plants. Put simply, this made it possible to specify an "acceptable" level of pollutant load based on the sensitivity of ecosystems to pollution. It also enabled researchers to estimate the reductions in emissions that were needed to avoid harm.

The second Sulphur Protocol was signed in Oslo in 1994 by 26 countries and the European Union (EU). A big change in this protocol was that it set different requirements for different countries. This differentiation between countries was intended to achieve the maximum environmental improvement for the minimum overall cost, calculated using advanced computer modelling and allowing for variations in nature's sensitivity to sulphur.

The Gothenburg Protocol

Further developments in computer modelling led to the 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, better known as the Gothenburg Protocol. This takes a collective approach to three environmental problems and the four pollutants that cause them: SO_2, NOx, NH_3 and NMVOCs.

The protocol sets binding national emission ceilings for the four air pollutants, to be achieved by 2010 and not to be exceeded thereafter. It also sets emission limit values for power plants and motor vehicles, for example, as well as requirements for fuels.

Following several years of negotiations the Gothenburg Protocol was revised in 2012. In addition to the four previously mentioned air pollutants, small particles ($PM_{2.5}$) were added to give further protection to human health. Emission ceilings were replaced with commitments for percentage reductions in national emission from the base year 2005 to the target year 2020. Emission limit values for different sectors were also updated and tightened.

2. EU air quality policy

The conventional EU environmental policy approach is to use technical requirements to regulate activities such as emissions from vehicles and large combustion plants. The requirements imposed are usually based on well-established technologies, and therefore rarely lead to innovative technological or system change.

In the mid-1990s, the Air Convention's work on critical loads and computer modelling to identify cost-effective measures began to have an impact on the EU's air pollution control work.

Following an initiative by Sweden, which joined the EU in 1995, the European Commission developed a strategy to stop acidification, which was presented in 1997. It was based on a long-term environmental objective adopted back in 1993 in the EU's fifth environmental action programme – namely that the critical loads for acidification should not be exceeded. The acidification strategy proposed an initial interim target for reducing emissions of acidifying air pollutants (SO_2, NOx and NH_3) by 2010 and a series of measures to achieve this.

The Emission Ceilings Directive

The acidification strategy was followed by an ozone strategy, and together these formed the basis for a new EU Directive adopted in 2001, setting binding national emission ceilings for four harmful, acidifying and eutrophying air pollutants to be achieved by 2010 – following the same line as the Gothenburg Protocol.

The Emission Ceilings Directive, which was updated and revised in 2016, is the most important overarching EU directive for reducing emissions of air pollutants. The Directive assigns national emission reduction targets to each country, to be achieved in two stages (2020 and 2030) for the five pollutants SO_2, NOx, NH_3, NMVOC and $PM_{2.5}$. The first three are acidifying; NO_2 and NH_3 contribute to eutrophication; while NOx and NMVOC act together to form ground-level ozone, and all five contribute to harmful levels of airborne particulates.

The Directive also sets targets for reducing acidification, nitrogen eutrophication, ground-level ozone and human exposure to harmful particulates in the air by 2030.

In addition to the Emission Ceilings Directive, there are a number of EU rules that limit emissions of air pollutants from various sources, including vehicles, combustion plants and industry. These rules are usually updated and revised every 5 to 10 years.

Air quality and health

In the 1970s and 1980s the main goal of air quality policy was to mitigate harm to the natural environment, particularly fish deaths and forest dieback, but also biodiversity. During the 1990s our understanding of the harmful effects of air pollution on human health improved. The fact that these health impacts could also be more easily valued in economic terms helped to further strengthen the case for reducing emissions.

Experts at the European Environment Agency (EEA) have estimated that elevated levels of small particles ($PM_{2.5}$) in 1990 caused around one million premature deaths annually in the EU. Thanks to emission reductions, this figure was halved by 2005. The socio-economic cost of excess mortality and illness caused by $PM_{2.5}$ was estimated at between EUR 385 and 1088 billion in the EU in 2005.

tion, but are also produced by the evaporation of petrol and solvents. Some VOCs are used as solvents in industrial processes and in paints and varnishes.

Particulates: $PM_{2.5}$ and PM_{10} are measures of particulate matter levels, which, put simply, give the mass of particles in the air that are smaller than 2.5 and 10 micrometres (µm) in diameter, respectively. When inhaled, these particles can penetrate deep into the lungs and cause short- and long-term adverse health effects. The larger particles are formed by the abrasion of road surfaces due to studded tires, for example, while the smaller particles mainly come from various forms of combustion and industrial processes. Some small particles, such as ammonium sulphate and ammonium nitrate, are also formed through reactions between SO_2, NOx and NH_3. A large proportion of the small particles, even in urban background air, are transported over long distances.

Ground-level ozone (O_3) is formed in polluted air through the action of sunlight. Nitrogen oxides and VOCs from natural and human sources contribute to the formation of ground-level ozone. Ozone is long-lived in the atmosphere and can travel long distances. It can be broken down by nitrogen oxide from vehicle emissions, so ozone levels can be lower in cities than in rural areas.

Hydrocarbons are a large group of substances made up of just carbon and hydrogen. They include compounds such as benzene, which is the simplest aromatic hydrocarbon. A subset of aromatic hydrocarbons are polycyclic aromatic hydrocarbons (PAHs), such as benzo(a)pyrene. Several hydrocarbons are directly harmful to health, including causing cancer. Benzo(a)pyrene and other PAHs are formed during incomplete combustion. Small-scale wood burning and traffic are the main sources of benzo(a)pyrene in the air in Sweden.

Source: Swedish Environmental Protection Agency.

Since 1979, the Air Convention's international negotiations on reducing emissions of air pollutants have been held at the UN building in Geneva, Switzerland.

In 1996, the EU adopted a framework directive on air quality, which was later supplemented with additional directives setting binding air quality standards for a number of pollutants. Most of these directives were replaced by a new consolidated air quality directive, adopted in 2008.

Although EU air quality standards are significantly weaker than the science-based guideline values developed by the WHO to protect human health, they are still exceeded in many places. It has gradually become clear that many EU member states have not taken the necessary emission control measures to meet the air quality standards, in particular for PM_{10} (to be met in 2005) and NO_2 (to be met in 2010). These countries face heavy fines if they are found guilty by the European Court of Justice. In autumn 2022, the EU Commission had brought 28 legal cases (involving 18 countries) to the Court of Justice for exceeding air quality standards.

Following a two-year review of the Air Quality Directive, the Commission presented a proposal to revise it in 2022, aiming to improve implementation and bring the limit values closer in line with WHO recommendations.

According to the European Environment Agency's 2022 report, more than 90 percent of the EU's urban population lives in areas where levels of the pollutants $PM_{2.5}$, NO_2 and O_3 exceed the guidelines for good air quality set by the WHO.

3. Air pollution from international shipping

The primary fuel used by international shipping since the 1960s has been high-sulphur heavy fuel oil, a type of refinery residue with an average sulphur content of between 2.5 and 3 percent. This compares to a maximum of 0.001 percent for diesel fuel used by inland shipping and trucks in the EU. The combustion process in the diesel engines of ships also produces high emissions of nitrogen oxides. Despite this, no pollution limits applied to shipping for a long time, so emissions continued to rise and became increasingly significant as land-based emissions began to decline in the 1980s.

In response to their acidification problems, Norway and Sweden began pushing the UN International Maritime Organization (IMO) to set limits for sulphur emissions in the late 1980s, which led to a new protocol (Annex VI) in 1997. However, there was strong resistance to setting requirements for shipping, and the new rules did not come into force until 2005. In the same year, the EU's Sulphur in Fuels Directive was extended to cover marine heavy oils, setting sulphur limits similar to those in IMO Annex VI.

Sweden realised it would take time to achieve effective limits globally, and took matters into its own hands on by introducing a system of environmentally differentiated fairway and port charges in 1998. Briefly, this meant that ships using low-sulphur fuel and NOx scrubbers paid less, while more polluting ships had to pay more – which turned out to be an effective way of reducing sulphur levels in particular.

Weak requirements and slow progress

On the whole, the 2005 IMO and EU requirements were weak and largely ineffective, with the exception of the sulphur requirements in special sulphur emission control areas (SECAs). The only SECAs at that time were the Baltic and North Sea, where marine fuels with a sulphur content of more than 1.5 percent were no longer permitted after 2006/2007.

After the EU and the US belatedly recognised the rising contribution of shipping to harmful levels of air pollutants, new negotiations began at IMO in 2005 to revise and stiffen Annex VI, which led to tougher new requirements in 2008. For global shipping, the sulphur limit was lowered in two steps, from 4.5 to 3.5 percent from 2012, and then to 0.5 percent from 2020.

In SECAs, the limit was reduced to 1.0 percent from 2010 and then to 0.1 percent from 2015. In addition to the Baltic Sea and the North Sea, the entire coastline of the US and Canada are now SECAs. And in 2022, the IMO agreed that the Mediterranean will also become a SECA from 2025.

Limits for nitrogen oxides were also stiffened in 2008, and emissions from ships built after 2011 must be about 20 percent lower. Within special NOx control areas, newly built ships must reduce NOx emissions by around 80 percent. NOx control areas were introduced around North America in 2016, and in the Baltic and North Sea in 2021.

In 2000, ships in the sea around Europe emitted 4.1 million tons of NOx and 2.2 million tons of SO_2. The new sulphur limits are finally paying off, and by 2020, sulphur emissions from shipping had fallen by almost 90 percent. But the weaker NOx limits have only reduced emissions by about a third. If no new NOx limits are implemented, there is a risk that NOx emissions from shipping will rise, which could mean that by 2030 international shipping around Europe would emit around the same amount of nitrogen oxides as all land-based sources in the 27 EU member states.

4. Changes over time

Since pollution does not recognise any borders, air quality is a highly international issue. International cooperation on research and policy measures under the Air Convention and the EU has been laborious and slow – too slow, according to the environmental movement. But it has also delivered measurable and visible results.

Ships are much bigger emitters of air pollution than most people think. After decades of international negotiations, sulphur emissions from shipping have at last been significantly reduced. But it is still vital to agree and implement measures that also reduce NOx emissions quickly and effectively.

Across Europe, sulphur emissions from land-based sources have fallen by more than 90 percent from their peak, around 1980, while NOx and NMVOC emissions have been more than halved. In contrast, ammonia emissions, mainly from agriculture, have only fallen marginally, by about 16 percent. The EU has done slightly better than Europe as a whole, as shown in Figure A on the next page.

These emission reductions have led to a sharp drop in the deposition of acidifying sulphur and significantly fewer exceedances of the critical load for acidification in Europe, from 39 percent of the ecosystem area in 1980 to less than 4 percent in 2020. In Sweden, the area of exceedances fell from 50 to 2 percent between 1980 and 2020. See Figure B, which also shows the change in the EU-27.

Because emissions of nitrogen compounds (NOx and NH_3) have not fallen nearly as much as sulphur, the improvement in eutrophication is much more modest. As shown in Figure C, the share of ecosystems in Europe subjected to nitrogen overload has only fallen from 80 to 62 percent between 1980 and 2020.

In the EU, more than 1,000,000 square kilometres of sensitive ecosystems were still exposed to nitrogen overload in 2020, and more than 100,000 square kilometres to acid deposition overload, resulting in damage to biodiversity, among other things.

Levels of ground-level ozone vary significantly from year to year, partly depending on weather and temperature. Between 2000 and 2020, critical loads were exceeded over 75–95 percent of agricultural land and 60–98 percent of forestry land in the EU.

5. The future

The ability to breathe clean air is a fundamental human right, as formally acknowledged by the UN General Assembly as recently as 2021. But as explained above, most of Europe's (and the world's) population, particularly those in cities, are still exposed to unhealthy levels of air pollution, mainly $PM_{2.5}$, NO_2 and O_3.

The Air Convention and the European Commission have both developed forecast scenarios up to 2050, assuming full implementation of all current air quality laws and regulations, including the EU Green Deal (with its Zero Pollution Vision and Fit For 55 climate policy). Although air pollution emissions are expected to continue falling, the scenarios show alarmingly clearly that neither health nor environmental objectives will be met by 2030, and most likely not even by 2050. It is therefore clear that more needs to be done.

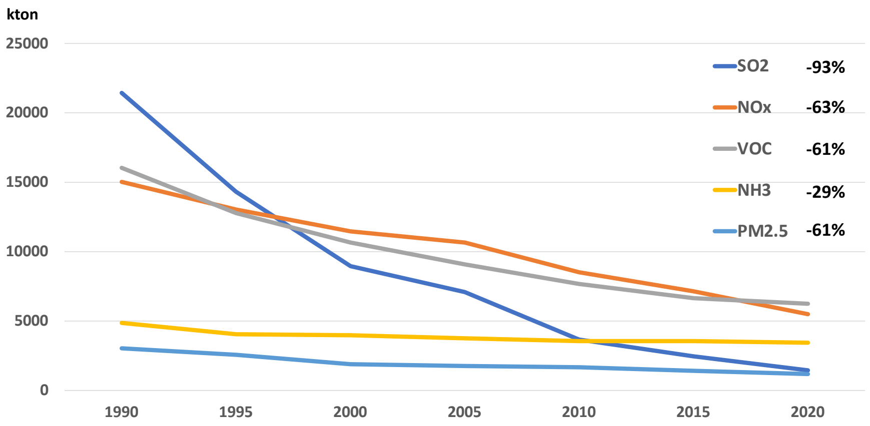


Figure A. Air pollutant emissions in the 27 EU member states fell between 1990 and 2020. While emissions of sulphur and nitrogen oxides were cut by 93% and 63% respectively, ammonia emissions have only fallen by 29%. (Emissions in thousands of tonnes.)

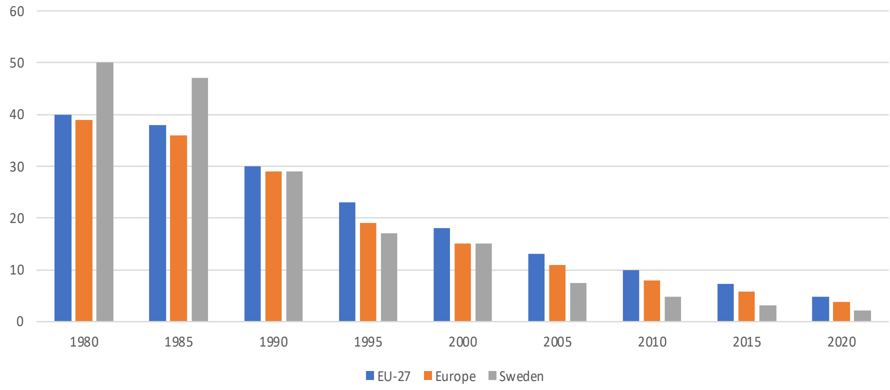


Figure B. The bars indicate the percentage of ecosystems in Sweden, the EU and Europe that are subject to overload by acidifying pollutants – i.e. where critical loads for acidification are exceeded. Due to sharp reductions in emissions – primarily of sulphur – in Europe, the overloaded area shrank significantly between 1980 and 2020.

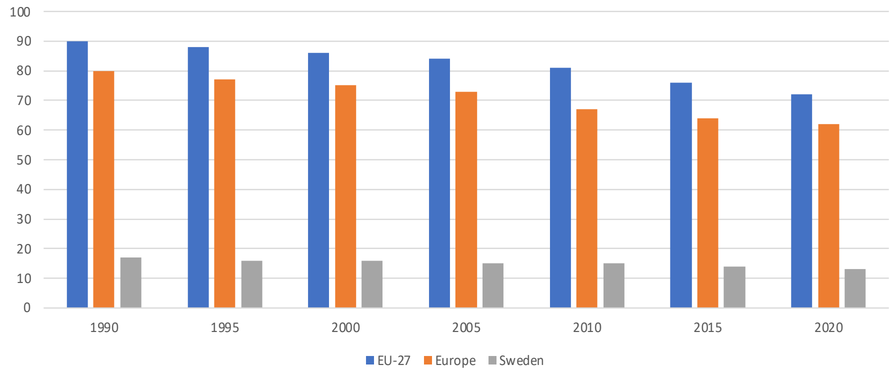


Figure C. The bars indicate the percentage of ecosystems in Sweden, the EU and Europe that are exposed to overloading by eutrophying air pollutants – i.e. where critical loads for over-fertilisation with nitrogen are exceeded. There has been some improvement since 1990, but because emissions of nitrogen compounds (NH_3 and NOx) are still too high, more than 60% (over 1,000,000 square kilometres) of sensitive ecosystems in the EU are still subject to overloading.

FACT BOX: Health effects of air pollution in Sweden

Air pollution can cause cardiovascular and respiratory diseases and has both acute and chronic effects on health. Based on annual average concentrations in urban and regional background air in 2019, IVL Svenska Miljöinstitutet AB and Umeå University have calculated on behalf of the Swedish EPA that air pollution causes more than 6,700 premature deaths in Sweden annually. Each death is estimated to correspond on average to a loss of 10 years of life.

The health effects of high levels of NO_2 and $PM_{2.5}$ are estimated to cost society around SEK 168 billion each year. On days with high levels of air pollution, more people fall ill and seek medical care. Productivity losses due to sick leave alone are estimated to cause economic losses of about 0.02% of GDP in Sweden.

The results show that more than 80 percent of the Swedish population is exposed to levels of $PM_{2.5}$ above WHO guideline values for air, and just over 10% are exposed to levels of NO_2 and PM_{10} above the recommended levels.

Source: IVL Svenska Miljöinstitutet AB and Umeå University (2022). "Quantification of population exposure to NO_2, PM_{10} and $PM_{2.5}$, and estimated health impacts 2019".

At the time of writing, the EU is working on reviewing, revising and tightening several air pollution regulations, including directives on air quality, industrial emissions, vehicle emissions and emission ceilings. The Air Convention has just completed a review of the 2012 Gothenburg Protocol and a draft revision will be negotiated over the next few years.

Air quality policy is closely linked to several other policy areas, including the climate, energy, transport, industry and agriculture.

The EU's Fit for 55 climate package will be finalised in 2023, and the new climate requirements will spur on the reduction of greenhouse gas emissions over the next decade, mainly from the energy, industry and transport sectors. The declining use of fossil fuels (coal, oil, gas) will further reduce emissions of air pollutants, mainly SO_2, NOx and $PM_{2.5}$.

Future scenarios show that additional measures will be needed to meet environmental objectives, especially to reduce emissions of:

- Ammonia and methane from animal husbandry (meat and dairy products);
- Nitrogen oxides from international shipping and urban road traffic;
- Particulates from traffic wear on road surfaces, tyres and brakes;
- Particulates from small-scale solid fuel burning (wood and coal for domestic heating).

So despite more than 50 years of efforts to reduce air pollution, we are still a long way from achieving the basic environmental objectives set by the Air Convention and the EU: to prevent exceedance of critical loads for the protection of ecosystems and protect human health from air pollution.

Climate, air pollution and landscape

Climate change is often seen as the leading environmental issue of our time. There is a lot of truth in this, but the threats to biodiversity and the Earth's ecosystems are a global issue of equal magnitude. In some cases, there are strong links between climate impacts and ecosystem changes. There are also important links between the climate and air pollution. In this chapter, we explore in more detail how these environmental problems interact.

Greenhouse gases and air pollution – similar but different

There are many links between climate change and air pollution. One of the strongest is that in many cases – but not all – greenhouse gases and air pollutants have the same emission sources. Key air pollutants such as NOx and the greenhouse gas CO_2 are emitted when fossil fuels are burned, in car engines for example. Many industrial processes and various forms of energy generation also produce emissions of air pollutants and greenhouse gases. This means that measures to reduce one type of pollution will also help to reduce emissions of the other. When we look at the costs of action to improve the environment it is important to consider all the potential benefits. Otherwise these measures may look less "profitable" than they actually are in relation to the cost.

In the past, huge quantities of acidifying sulphur were emitted along with even larger quantities of CO_2 from large power plants that burned coal or oil. One example is the oil-fired power plant in Stenungsund, which was commissioned in 1959 and was one of Sweden's largest sources of sulphur emissions in the 1960s, since the oil had a very high sulphur content that was emitted without treatment in the early years. In 1968, a law was passed prohibiting the use of oil with a sulphur content higher than 2.5 percent – a very high level! – but before that oil could have a sulphur content of up to 4 percent. Today, only about two percent of electricity generation in Sweden comes from fossil fuels, and sulphur can be effectively removed from the fuel or flue gases. The measures taken have thus reduced both emissions of carbon dioxide and air pollutants such as sulphur dioxide. Some units at Stenungsund power plant are now designated as back-up power generation and have been mothballed for many years.

Sometimes the link between air pollutant emissions and greenhouse gases is less obvious or non-existent. Emissions of ammonia from manure spreading and animal husbandry – which contribute to several environmental problems including eutrophication and acidification – are not directly linked to CO_2 emissions, although animal husbandry often uses fossil fuels, for example for transport. Emissions of other greenhouse gases such as methane and nitrous oxide can also result from the processing of livestock manure.

Stenungsund, with the four chimneys of the old oil-fired power plant in the background. The power plant was once one of the largest sources of acidifying SO_2 emissions in Sweden.

Short-lived climate-changing air pollutants

In most cases, greenhouse gases persist in the atmosphere for a long time. They remain there for tens or hundreds of years. In contrast, methane is a rather short-lived greenhouse gas with an average lifetime in the atmosphere of about 10 years, while nitrous oxide and carbon dioxide remain in the air for much longer. Air pollutants tend to be much more short-lived, staying in the atmosphere for a few hours or up to a few weeks after being emitted. The harm they cause is often linked to the fact they are reactive and are absorbed by plants, react with our lung tissues, and fall as precipitation after reacting chemically in the atmosphere, etc. Their reactivity means they are short-lived. But some air pollutants are also greenhouse gases or contribute to the formation of climate-changing particles. Ground-level ozone is an example of the former. Ozone is formed in the air closest to the Earth through the action of sunlight on pollutants such as NOx and VOCs. Ozone is a significant greenhouse gas that is also highly reactive and therefore harmful to health, plants and materials.

Sooty flare from Borealis in Stenungsund on 25 December 2018.

Particulates – a complex and important problem

Particulates are a type of air pollutant considered to have by far the greatest impact on human health globally. The subject of airborne particulates in the air is quite complex, as they are emitted from many different sources (including various types of combustion and through tyre wear and road surface wear by vehicles). They can also be formed in the atmosphere by other pollutants and are deposited on plants and soils in different ways. Particles are also emitted into the atmosphere by natural processes, such as wind action on fine soil or wave action on salt spray. Different particles can also be harmful in different ways. For example, the size of the particles is important – very small particles penetrate deeper into the respiratory tract and cause more harm. Some particles can be carried long distances in the air, while others are deposited close to their source.

What's more, particles can also affect the climate. Here too, different types of particles have different effects. Soot particles are relatively black, which means they absorb solar radiation and contribute to the greenhouse effect. Other particles, such as those formed by sulphur and nitrogen in the atmosphere, are whiter. This means they reflect sunlight instead and hence reduce warming. Particles can also have indirect effects on the climate. Particles in the air act as condensation nuclei for the water droplets that form clouds. If there are more particles in the atmosphere it affects cloud formation and the properties of clouds, which in turn affects how they reflect sunlight. Clouds with lots of small droplets reflect more sunlight (they appear whiter) than those made up of fewer but larger droplets.

Particles in the atmosphere therefore have a big impact due to their harmful effects on health and their effects on the climate. And as we have seen, the effects of these particles vary widely depending on their size and chemistry.

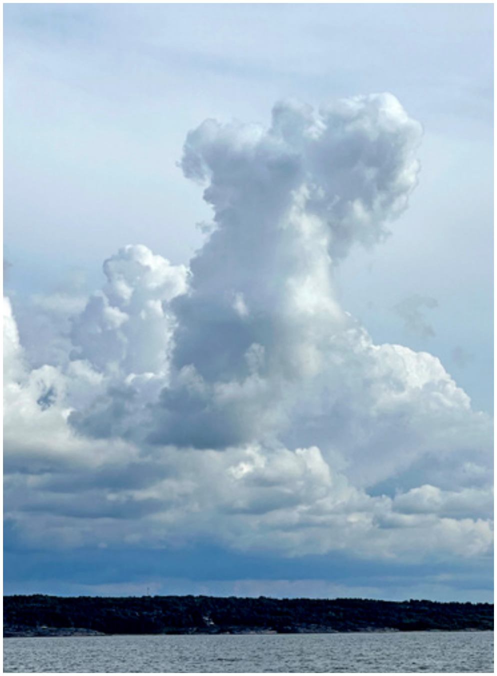
The 2018 heatwave

The summer of 2018 was marked by an unusually long period of very hot, dry weather. Climate models suggest that this type of extreme weather event is becoming more likely due to climate change. Prolonged intense heat has many consequences, because so many processes – biological or otherwise – are highly dependent on temperature. Very high temperatures, as well as very low ones, can have significant effects on our health. As we all know, heat and drought affect vegetation and can have an impact on crops as well as non-agricultural ecosystems. This has a knock-on effect on animals via the food chain, and in the longer term climate change will lead to changes in the composition of plants and animals due to the differing abilities of species to adapt to drought, extremes of temperature and changing conditions.

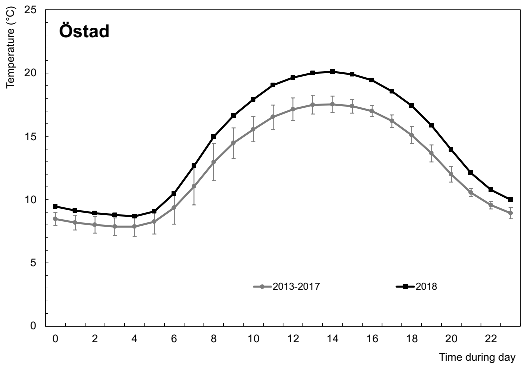
There are also important links between air pollutants, their reactions and effects, and the climate or weather. The chemical reactions that form ground-level ozone are accelerated by higher temperatures. So it is not surprising that higher levels of this toxic gas occur when it is warmer. This was also the case during the 2018 heatwave: ground-level ozone levels were higher than in previous, cooler, summers. That's not all. Ozone levels during the heatwave were even higher than would be expected from the temperature alone. This was probably due to the drought. When the soil and air become very dry, plants reduce transpiration by closing their stomata – small pores on the surface of leaves that control the uptake of carbon dioxide for photosynthesis and release of water vapour – to avoid the risk of wilting. The uptake of harmful ground-level ozone through the stomata of plants is reduced during severe drought. Because uptake by plants is important for removing ozone formed in the air, the effect is that ozone builds up in the atmosphere, leading to higher levels and greater risk to our health.

The spruce bark beetle – a small bug with a big impact

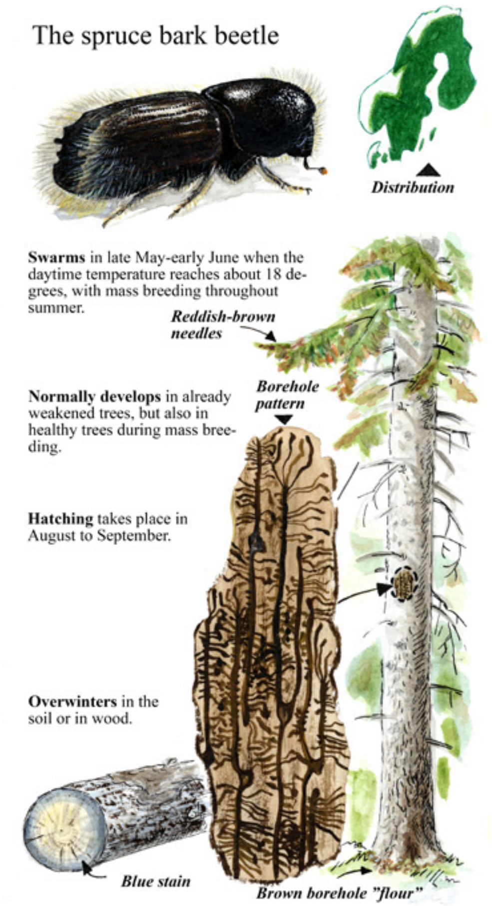
One clear example of how land use, ecosystems and the climate interact is the growing risk of infestation by the spruce bark beetle, a small beetle that can appear in very large numbers under certain conditions and is the biggest threat to spruce trees in northern and central Europe. The extent of infestation, which is sometimes very widespread and kills many trees, depends on several factors. The spruce bark beetle mainly attacks trees that are already weakened, for example by drought or wind damage. Summer droughts and storms



Particles released into the air affect the properties of clouds, such as their ability to reflect sunlight, which in turn affects the climate.



Temperatures in summer 2018 were significantly higher than in the previous five-year period.



are likely to increase as climate change progresses. Rising temperatures also benefit spruce bark beetles by allowing them to breed faster each summer.

Before the landscape in south-western Sweden was transformed by farming into pasture land or arable land, spruce trees were not nearly as widespread as today. Oak and pine were much more common. When reforestation began over a hundred years ago, large numbers of spruce trees were planted, and still are today. Dense plantations of spruce have become the rule over large areas. These monocultures, which contain very few other tree species, contribute to more extensive bark beetle damage. A more diverse forest with a greater variety of trees reduces the extent of damage and is also believed to favour the natural enemies of spruce bark beetle. The spruce bark beetle is sometimes referred to as an invasive species, but this is not true. It is a natural resident of our forest ecosystems that is having more impact due to the planting of spruce monocultures, and problems of this type are growing as the climate gets warmer, which also leads to more severe summer droughts and increased storm damage. The spruce bark beetle has also caused extensive damage at Gårdsjön in recent decades.

In large parts of Sweden spruce were planted after the land had been cleared, resulting in monocultural forests with trees of the same age and species.

How will the climate at Gårdsjön develop?

It is likely that climate change will lead to significant changes in the environment around Lake Gårdsjön. Temperature, precipitation and their annual patterns always have a big impact on nature. How far a species can spread depends greatly on the climate, as does the competition between existing species, but the choices we humans make in how we use the land, such as which tree species to plant or whether to drain the soil, also have a major impact on how the landscape develops. There are large areas in Sweden that have been drained, for example to create new arable land or to favour forestry. Wetlands that contain peat become significant sources of greenhouse gases if they are drained and the peat starts to decompose, releasing CO_2 and other greenhouse gases. Many people therefore believe that the landscape should be "rewetted" through ditching and other measures to restore wetlands. Another benefit is that this slows down the flow of water through ecosystems and reduces the risk of flooding. It would also benefit biodiversity.

The Swedish Meteorological and Hydrological Institute (SMHI) has developed a climate scenario service. You can use it to see how the climate is likely to develop over different time spans, emission scenarios and seasons, according to the current state of knowledge. On the whole, forecasts for the area of Bohuslän in which Gårdsjön lies show that it will become warmer, and that precipitation is likely to increase (see figure on page 7 showing the precipitation trend for the west coast). Precipitation is forecast to increase more in winter than in summer, which is important for vegetation, which needs most water in summer. It should also be mentioned that increased precipitation does not necessarily mean a wetter climate in terms of more run-off from the land or improved water availability for plants if temperatures rise. This is because a warmer climate leads to more evaporation, which offsets the effect of increased precipitation. So there is a delicate balance between different processes. In addition, statistical trends of this type do not reveal the risk of more frequent extreme weather events. As already mentioned, heat waves and other extreme weather events are likely to increase with climate change.

Despite milder winters, it is occasionally possible to ski on Gårdsjön (A). Lingonberries in bloom, May 2023 (B). Campfire at Friluftsfrämjandet's shelter at Gårdsjön (C). Gårdsjön is a starting point for canoe tours and part of a system of lakes (D).

The mercury problem in Sweden and at Gårdsjön

Mercury (Hg) occurs naturally in the environment due to weathering of mercury-containing minerals and emissions from volcanic eruptions, but emissions from coal burning, small-scale gold mining, waste incineration and some smelters have led to much higher concentrations of mercury in the environment. During combustion, a large proportion of the mercury is released in gaseous form and remains in the atmosphere for much longer than pollutants such as SO_2 and NOx, so it can be carried over long distances before being oxidised and deposited on plants, soil and water. Deposited mercury can also return from an ecosystem into the atmosphere and spread further, meaning that the actual distances between emissions and their uptake by ecosystems can increase.

The majority of mercury deposited from the air in Sweden originates from other countries. Most of the mercury in soil is bound to organic matter, and the vertical distribution of mercury in soil often matches the distribution of humus in the soil profile. Organic matter in forest soils has been accumulating mercury from atmospheric deposition for a very long time, and for many boreal catchments the main source of mercury is long-range atmospheric transport.

Most of the deposited mercury is inorganic mercury and only a small proportion is the highly toxic form of methylmercury (which accounts for about one percent of total mercury in the soil). Methylmercury can also be formed by the methylation of inorganic mercury by microorganisms in soil, water or sediment. Methylation is favoured by increased decomposition of soil organic matter under anaerobic or low-oxygen conditions.

Methylmercury is the main form of mercury that accumulates in organisms and bioaccumulates in the food chain – it becomes more concentrated at each stage, e.g. from bacteria to plankton, through invertebrates, to herbivorous fish and eventually predatory fish. In a large proportion of Swedish lakes, the methylmercury content in fish such as pike and perch is above the food limits set by the WHO.

Mercury has been accumulating in humus in forest soils over many decades.

Hg budget at Gårdsjön

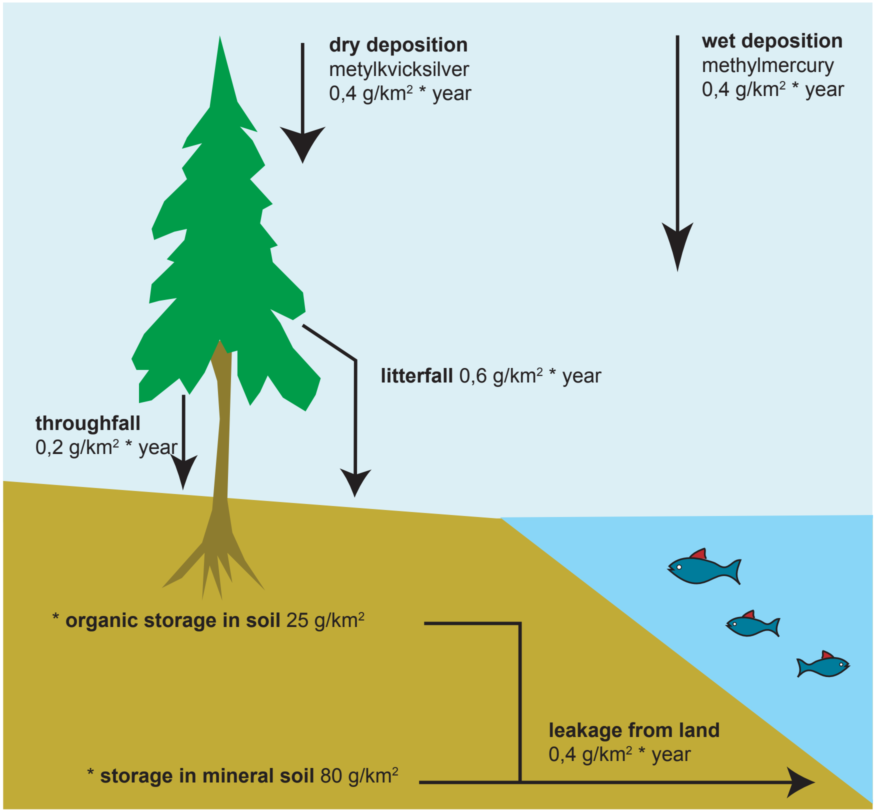
Establishing a budget requires many measurements, but also gives us an understanding of the flows and existing pools. This is necessary to assess how measures to reduce deposition could affect mercury levels and flows in ecosystems, and how measures should be targeted.

Gårdsjön was one of the first areas in the world where vital Hg budget parameters were measured across an entire catchment area – deposition, run-off, and concentrations in forest soil at different depths. Innovative methods were also used to measure methylmercury pools and transport.

The main conclusion is that there are large deposits of mercury in the soil which only change minimally as a result of precipitation or leaching. The same is true for methylmercury, but at considerably lower levels. Regarding the levels in fish, the key factors are the mercury level in run-off water that reaches the lake, and direct deposition on to the lake surface. Despite the very low levels in run-off, this is a large and significant source of contamination of aquatic ecosystems.

The large deposits of mercury in soils also mean that even the relatively small changes in leaching into run-off that can occur during forestry, for instance, can have a large influence on the total mercury load in the lake and hence on mercury levels in fish.

Atmospheric deposition, soil pool and leaching of methylmercury from a forest ecosystem into a lake.



What causes leaching?

During felling in spring 1999 in one of the catchment areas around Gårdsjön (designated F2 and previously used as a research site), timber was transported across the upper parts of another catchment area where measurements were ongoing (reference area F1), causing deep wheel ruts in both catchment areas. Total mercury and methylmercury levels were analysed in the stream water by monthly sampling, and in autumn 1999 values of up to 2.5 nanograms per litre (ng/l) were measured – about 50 times higher than the level of methylmercury previously measured in the run-off.

In the felled catchment area the highest levels of methylmercury were even greater and from 2003 to 2005 the concentration of methylmercury ranged from 0.5 to 5 ng/l, between 10 and 100 times higher than in the years before 1999.

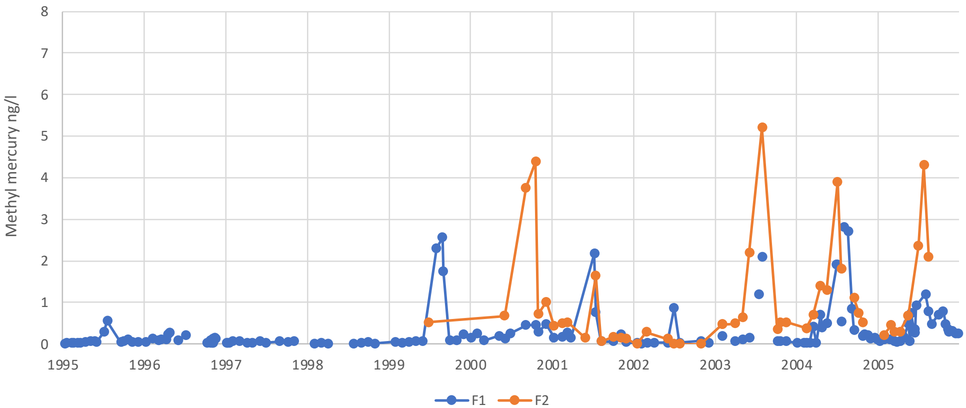
The mechanical damage caused by moving timber led to large changes in water flows and soil organic matter. This, combined with the increased solubility of methylmercury in water, led to elevated leaching of methylmercury into run-off water over many years. Increased leaching of methylmercury from forest soils into lakes means increased uptake by fish. Several studies have shown that bioaccumulation of methylmercury through the food chain increased in lakes downstream of the felled forest areas.

Sweden has since long reduced emissions of mercury into the air and water, as in the rest of Europe and North America. Globally, however, emissions remain relatively steady due to increases in Asia and from small-scale gold mining in many regions. However, methylmercury levels in fish from forest lakes have not fallen in parallel with Swedish emissions. One key reason may be modern forestry, which uses heavy machines to fell trees and haul them out of the forest. This disturbs the humus layer in the soil, resulting in increased leaching of methylmercury from the organic matter. The high levels of methylmercury in fish in regions that use industrial forestry practices, combined with ongoing long-range transport and deposition, may lie behind the widespread distribution of high levels of methylmercury in fish in Sweden.

FACT BOX: Measuring mercury levels

- Hg occurs naturally in water at very low concentrations – usually around one or a few nanograms per litre (equivalent to grams of Hg per million cubic metres) of water. Methylmercury makes up about 1–5% of this.
- Measuring such low levels is challenging, and reliable methods only became available in the 1980s.
- As a result of bioaccumulation, levels in fish are much higher (of the order of one milligram per kilogram) and thus much easier to measure.

Methylmercury levels in run-off from areas F1 and F2 increased after felling and hauling trees.



Literature & websites

Recommended websites

www.artfakta.se
www.artportalen.se
www.eea.europa.eu/en/topics/in-depth/air-pollution (European Environment Agency)
www.airclim.org (Air Pollution & Climate Secretariat)
http://www.gardsjon.org (Gårdsjöstiftelsen)
www.naturvardsverket.se (Swedish Environmental Protection Agency)
https://unece.org/environmental-policy-1/air (Air Convention)

Gårdsjöstiftelsen

Gårdsjöstiftelsen (the Lake Gårdsjön Foundation) is a non-profit foundation established in 1991 by Hensbackastiftelsen, IVL Svenska Miljöinstitutet AB and Stenungsund Municipality. The board includes representatives from IVL, Hensbackastiftelsen, Stenungsund Municipality and environmentally concerned individuals.

The role of the foundation

Gårdsjöstiftelsen aims to provide information on air pollution and its harmful effects on water, forests and soil, based on research in and around Lake Gårdsjön. Its work is aimed at decision-makers in the private and public sectors, politicians, environmental experts, researchers, schools, university students and the general public, in Sweden and abroad.

gårdsjö
stiftelsen

Recommended reading on air pollution, acidification and climate

Anderson, F. & B. Olsson 1985. *Lake Gårdsjön. An acid forest lake and its catchment*. – Ecological Bulletins 37. Stockholm.

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Bernes, C. (ed.) 2001. *Läker tiden alla sår?* – Naturvårdsverket Monitor 17, Stockholm.

Bertills, U. & T. Näsholm (ed.) 2000. *Effekter av kvävenedfall på skogsekosystem*. – Naturvårdsverket Rapport 5066. Stockholm.

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Havs- och vattenmyndigheten 2020. *Målvattendragsundersökningen 2010 - 2016. Bedömning av surhet och försurning i kalkade vattendrag*. – Havs- och vattenmyndigheten. Rapport 2020:29, Göteborg.

Havs- och vattenmyndigheten 2021. *Kalkningsåret 2021. En redovisning av nyckeltal*. – Havs- och vattenmyndigheten. Rapport 2020:29, Stockholm.

Havs- och vattenmyndigheten 2022. *Ingen övergödning. Fördjupad utvärdering av miljömålen 2023*. – Havs- och vattenmyndigheten rapport 2022:16, Stockholm.

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

Naturvårdsverket 2023. *Fördjupad utvärdering av Sveriges miljömål 2023*. – Naturvårdsverket Rapport 7088, Stockholm.

Naturvårdsverket 2023. *Frisk luft. Fördjupad utvärdering av miljömålen 2023*. – Naturvårdsverket Rapport 7067, Stockholm.

Naturvårdsverket 2023. *Bara naturlig försurning. Fördjupad utvärdering av miljömålen 2023*. – Naturvårdsverket Rapport 7069, Stockholm.

Naturvårdsverket 2023. *Begränsad klimatpåverkan. Fördjupad utvärdering av miljömålen 2023*. – Naturvårdsverket Rapport 7068, Stockholm.

Naturvårdverket 2023. *Luft & miljö 2023. Partiklar*. – Naturvårdsverket (mars 2023).

Pleijel, H. (ed.) 1999. *Marknära ozon, ett hot mot växterna*. – Naturvårdsverket Rapport 4969, Stockholm.

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Sveriges riksdag 2000. *Svenska miljömål – delmål och åtgärdsstrategier* Proposition 2000/01:130. – Riksdagens tryckeriexpedition, Stockholm.

Warfinge, P. & U. Bertills (ed.) 2000. *Naturens återhämtning från försurning*. – Naturvårdsverket Rapport 5028, Stockholm.

The Earth is more than four billion years old. The bedrock around Gårdsjön, consisting of granite and gneiss, is 1.7 billion years old. It's hard to grasp how long that is. The last ice age ended just 12,000 years ago. In a vanishingly small fraction of the Earth's history, less than 100 years, ecological systems, groundwater and lakes have been drastically changed by the effects of various pollutants. From a geological perspective, the soil layer in the forest around Gårdsjön is very young. It is also very thin and has little capacity to resist acidification. This is why the massive emissions of acidifying air pollution in the 20th century had such harmful effects on the soil, water and forest ecosystem around Gårdsjön. The same applies to thousands of similar lakes in Sweden and many other countries in the northern hemisphere. Since the 1980s, levels of acidifying air pollution in Europe have fallen, and soils, rivers and lakes across much of the previously acidified areas of Scandinavia are slowly recovering. But the danger is not over yet. Nitrogen deposition is still high, as are levels of ground-level ozone. This book offers an insight into some of the most challenging environmental problems that affect our lakes and forest ecosystems, along with the results of 50 years of research into the effects of air pollution on the ecosystems around Gårdsjön.

Gårdsjöstiftelsen welcomes you to Lake Gårdsjön!

gårdsjö stiftelsen