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Photo: Getty Images

Foreword

Air pollution is one of the largest environmental risks to human health. There are many different types of air pollutants, but particles from combustion, tyre wear and other sources have the largest negative effects of all air pollutants. Particles are present in all the air we breathe, in different sizes, shapes and compositions, and they can affect human health regardless of how high or low the concentrations are. It has long been well known that particles, smoke and soot are dangerous, but how much do we know about new types of particles or new sources?

Research gives us a better understanding of the factors that make particles dangerous and of what we need to do to prevent adverse health effects. Research on particles is therefore vital, and every year it contributes new knowledge about effects on health, the environment and the climate. But it is absolutely crucial that politicians and administrative organisations translate research findings into action and ensure that we achieve as ambitious a regulatory framework and implementation as possible, with a focus on impactful improvements.

Particles are monitored through the Swedish Environmental Protection Agency's national environmental monitoring programme and locally by municipalities. Monitoring trends in concentrations over time and knowing the sources of particles are crucial for developing effective measures. There are significant socio-economic benefits from reducing particle concentrations.

This report is part of the Swedish Environmental Protection Agency’s series Air & Environment within the national environmental monitoring programme. The report’s authors include stakeholders active within the national air quality monitoring and researchers and experts at universities, research institutes and public agencies. A great deal of knowledge exists about particles, and the aim of this publication is to convey some of this knowledge so that we can work together to achieve cleaner air.

Stockholm 2023-03-07

Stefan Nyström
Director of the Climate Action Department,
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What are particles and how do they affect us?

Airborne particles affect human health, the climate and the environment. Although concentrations of particulate matter in Sweden have decreased significantly in recent decades, much work remains to be done to minimise health impacts. A key challenge is that particles can differ widely in composition and size, which influences their impact on the climate and health.

Airborne particles – as the name suggests – are so small that they can remain suspended in the air. A more scientific term for airborne particles is aerosols, which include both solid and liquid particles and the mixture of gases that keep particles suspended. To stay airborne, the particles must be less than approximately 100 micrometres (one tenth of a millimetre). Larger particles fall quickly to the ground and are generally unable to be transported over long distances. The lower limit for the size of particles is usually set around 1 nanometre (one millionth of a millimetre), since smaller particles cannot be clearly distinguished from gas molecules.

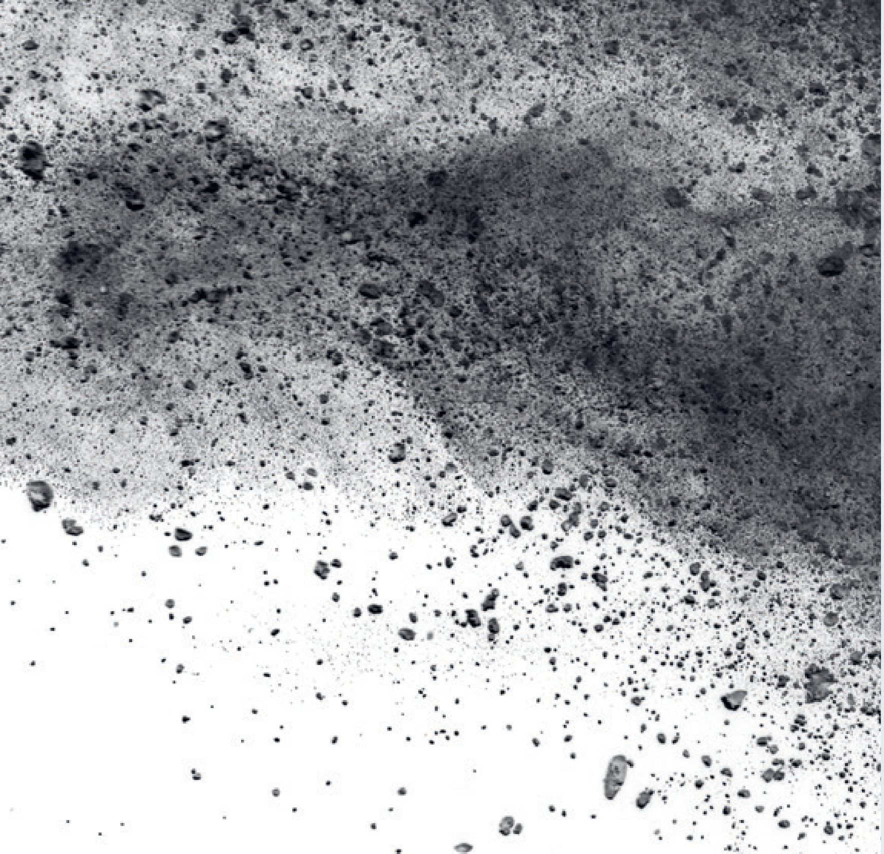
Differ greatly in size and composition

We distinguish between five orders of magnitude from the smallest to the largest aerosol particle. This is like comparing the head of a pin and the Globe Arena in Stockholm. The difference in mass (weight) is even larger, as many as 15 orders of magnitude. Bearing this in mind, it is not surprising that these airborne particles come from very different sources and have very different properties, chemical compositions, time suspended in the atmosphere, and effects on the climate, the environment and human health.

Figure 1. Particle size comparison

If the particles were about 30,000 times larger.

Photo: Adobe Stock



Airborne particles are significantly different from the trace gases and greenhouse gases that affect our air quality and climate. While every molecule of the greenhouse gas carbon dioxide looks similar, no two particles are identical. This makes it more difficult to assess the impact of airborne particles on human health and the climate.

Coarse and fine particles

In most cases the study of airborne particles is limited to particles with a diameter of less than 10 micrometres (one hundredth of a millimetre). This is because particles must be smaller than this to penetrate our lower airways and affect our health. Almost all particles are smaller than this diameter and make up the major fraction of the total particle mass.

Particle fractions and types

PM_{10} and $PM_{2.5}$ are the two most commonly used particle fractions. There are existing environmental quality standards for PM_{10} and $PM_{2.5}$ in ambient air, which aim to provide a level of protection against health effects that are unacceptable for society.

PM_{10} is the mass of all particles in a specific volume of air (usually in µg/m³, micrograms per cubic metre of air) with a diameter of less than 10 micrometres (µm), i.e. the particle sizes that can penetrate our lower airways.

$PM_{2.5}$ is the mass of all particles with a diameter of less than 2.5 micrometres in a specific volume of air. It was demonstrated in the 1990s that the relationship between particulate matter and health was even stronger if the measure $PM_{2.5}$ was used. The choice of 2.5 micrometres was rather coincidental due to shortcomings in the measurement technique available when monitoring started.

PM_1 or $PM_{0.1}$, with upper size limits of 1 and 0.1 micrometres, respectively, are sometimes used. Previously, TSP (Total Suspended Particle) mass that includes all particle sizes was also used.

Nanoparticles and ultrafine particles (UFP) do not have as well defined dimensions but are usually used for particles of less than 100 nanometres in diameter down to a few nanometres.

Soot can be expressed in many ways, including BC (Black Carbon), EC (Elemental Carbon) or previously BS (Black Smoke), depending on the measurement method used. OC (Organic Carbon) is the carbon in all non-soot organic (carbon-containing) compounds.

Particles are often divided into two ranges of size (known as modes or fractions):

- fine fractions (up to approx. 1–2.5 micrometres)
- coarse fractions (from 1–2.5 micrometres to 10 micrometres).

Particles are divided into these two ranges because they have completely different sources. Coarse fraction particles originate from mechanical processes (e.g. erosion and sea spray), where a bulk material breaks up into smaller pieces that can become airborne particles. Particles in the fine fraction are instead formed from smaller constituent pieces, usually gas molecules.

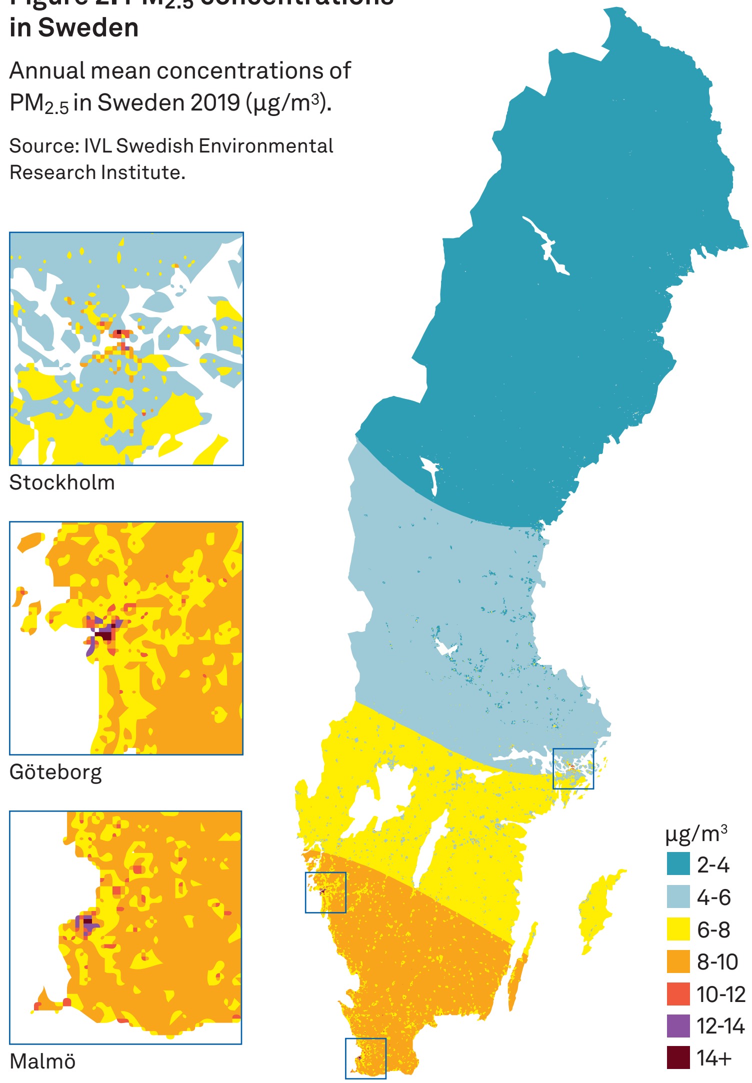
Different ways of measuring particles

There are several ways of describing the amount of particles in the air, depending on the purpose of the measurement and how it is performed. Typically, a measurement indicates the number of particles, their mass or their chemical composition. Sometimes the total area of the particles is of interest. Studies on human health tend to focus on the mass and chemical composition of particles while studies on the impact of particles on the climate mainly focus on particle numbers and particle size.

Figure 2. $PM_{2.5}$ concentrations in Sweden

Annual mean concentrations of $PM_{2.5}$ in Sweden 2019 (µg/m³).

Source: IVL Swedish Environmental Research Institute.



Lowest levels in northern Sweden

Annual mean concentrations of particles in regional background are lower than the environmental quality objective for both PM_{10} and $PM_{2.5}$. Concentrations fall as you move north in Sweden due to the fact that southern Sweden is considerably closer to large sources of emissions from the Continent and has a higher population density resulting in higher emission levels.

Photo: iStock

Burning wood increases the particle concentrations in the air.

Particles from different sources affect concentrations

About 90 per cent of all atmospheric particles have been created through natural processes. Some of the most important natural sources are sea salt, erosion, sand storms, grass and forest fires, volcanic eruptions and pollen. Airborne particles can also be produced secondarily from gases or by chemical and physical processes.

The remaining 10 per cent of particles in the air are generated by human activity, and emissions in some places in the world can be very large. Southern Sweden's proximity to the Continent plays a big role. Various sources of fossil fuel combustion in other countries, such as burning coal, car exhaust fumes and shipping, lead to high concentrations in Sweden due to long-range transport of air pollutants by wind systems. For example, this accounts for approximately 60 per cent of the $PM_{2.5}$ levels to which the average resident of Malmö is exposed.

In northern Sweden, however, the contribution from long-range transport is close to pre-industrial concentrations. There, instead, local traffic and wood burning for heating pose the greatest health risk. Old wood-burning stoves for heating individual households generate high emission levels in residential areas, and in valleys that suffer from poor air mixing, particle number concentrations or mass concentrations of $PM_{2.5}$ may be particularly high. In all major Swedish cities, exhaust emissions from cars contribute to high concentrations of small particles. These can amount to 20,000 to 30,000 particles per cubic centimetre of air (approximately the size of a sugar lump).

In Sweden, the use of studded tyres has an important impact on air quality. In cities with a

Photo: Aneta Wierzbicka

Dusty fields in Skåne on a dry day in April 2019.

high percentage of studded tyre use, concentrations of coarse particles (PM_{10}) can be very high in the spring when the road surface dries up and particles from wear of the asphalt surface caused by the studded tyres are blown into the air. On construction sites and on sandy, dry and bare fields, dust can also cause high levels of PM_{10}. Sometimes, even sand from the Sahara can be transported by wind to Sweden.

Dealing with high particle concentrations

Three-quarters of Europe's population live in cities, where road traffic is often the main source of air pollutants. In rural areas, heating homes with wood and coal is usually the biggest source of harmful pollution. As heavy industry and the energy sector have invested in improving air quality, the main focus has shifted to the transport sector. The EU's current vehicle emission standard, Euro 6, permits only a tenth of particulate emissions compared to Euro 3, which was introduced 20 years ago.

However, continuing to reduce particulate concentrations requires a broader range of measures, both by society and individuals. This includes increased use of district heating, promoting use of public transport, reducing speed limits and transitioning to cleaner vehicles, buses and trams, especially in large cities. Individuals can help by using friction winter tyres instead of studded tyres and reducing the use of stoves and wood boilers or using more modern equipment and more efficient burning techniques to minimise emissions.

The transport and energy sectors are a major source of particulate matter, but agriculture also

Photo: Johnér

Studded tyres cause abrasion of road surfaces. In the spring, road dust is resuspended in the air and produce high PM_{10} levels.

plays a role. Ammonia from fertiliser use creates secondary particles. In Europe, 95 per cent of the particles formed by gas-to-particle conversion originate in agriculture. Targeting this source of particulate air pollutants will require comprehensive measures from the agricultural sector.

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Further reading

Air startpage (naturvardsverket.se)

Quantification of population exposure to NO_2, PM_{10} and $PM_{2.5}$, and estimated health impacts 2019. IVL B2446 (diva-portal.org)

National monitoring programme - Particles (naturvardsverket.se)

Real-time data and preliminary statistics (naturvardsverket.se)

Europe's air quality status 2022 — European Environment Agency (europa.eu)

Regulations and particle monitoring in Sweden

Particle data were reported from **75 stations** in Sweden for 2021.

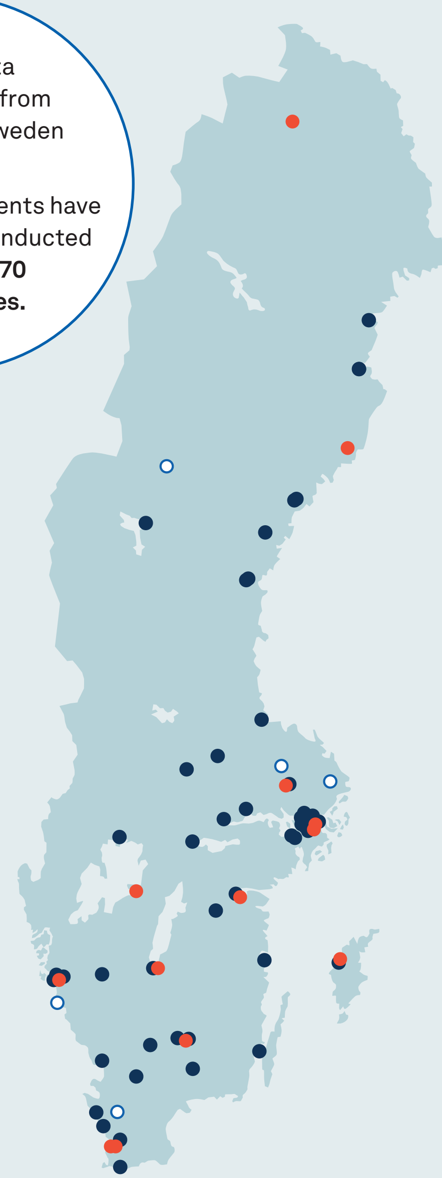
Particle measurements have previously been conducted in a total of **170 municipalities.**

Air quality is affected both by what we do at home and what happens hundreds of kilometres away since air pollutants travel by wind and respect no political borders. We have the potential of creating good air quality through ambitious legislation and international agreements. The availability of air quality data is important to many.

In Sweden, particle concentrations have been monitored for six decades, initially in the form of soot, but in the last 20 years measurements have shifted to PM_{10} and $PM_{2.5}$ in tune with changing regulations. There are currently around 70 measurement stations where particles are measured, the vast majority in urban areas since particles are primarily a traffic-related problem.

Monitoring is crucial

Monitoring particles in Sweden is primarily a result of the EU's demands on Sweden through the Ambient Air Quality Directive and Sweden's commitments to the UNECE's Convention on Long-Range Transboundary Air Pollution (CLRTAP), but also through the national environmental objective Clean Air and research activities.



● Traffic/street canyon
● Urban background
○ Regional background

Measuring stations in Sweden 2021

Particles are mainly measured in urban areas, but it is also important to map the contribution from long-range transport.

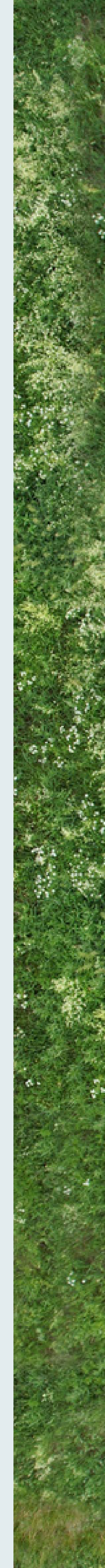


Photo: Irene Lehner

Four larger measurement stations

National particle monitoring in Sweden is performed at four large measurement stations in regional background (pictured Norunda in Uppland) within the Swedish EPA's national environmental monitoring programme. Here, PM_{10}, $PM_{2.5}$ and organic and elemental carbon (OC/EC in $PM_{2.5}$) are measured. At two of the stations soot, light absorption, particle size distribution and light scattering are measured.

Photo: Helena Sabelström

The measurements are mainly carried out in the most heavily polluted street canyons, but it is also important to monitor the general exposure in urban areas.

Table 1. The environmental quality standards, the environmental quality objectives and WHO's guideline values

Pollutant	PM_{10}		$PM_{2.5}$	
Mean value	**Day**	**Year**	**Day**	**Year**
Air Quality Ordinance 2010:477 – Environmental Quality Standards (EQS)	50 µg/m³ May be exceeded 35 times/year	40 µg/m³	-	25 µg/m³ and exposure reduction target
Ambient Air Quality Directive 2008/50/EC – Limit values	50 µg/m³ May be exceeded 35 times/year	40 µg/m³	-	25 µg/m³ and exposure reduction target
The Clean Air environmental objective – Specifications	30 µg/m³ May be exceeded 35 times/year	15 µg/m³	25 µg/m³ May be exceeded 3 times/year	10 µg/m³
WHO – Guideline values 2021	45 µg/m³ May be exceeded 3–4 times/year	15 µg/m³	15 µg/m³ May be exceeded 3–4 times/year	5 µg/m³

The municipalities have the main responsibility for assessing compliance with the environmental quality standards for PM_{10} and $PM_{2.5}$, i.e. the directive's limit values, in urban areas where concentrations are at their highest. Some municipalities also combine measurements with modelling. The Swedish Environmental Protection Agency supplements these assessments with various particle measurements in regional background, i.e. rural areas, and urban background within the frame-work of the national environmental monitoring programme. All local and national data are reported to the Swedish Environmental Protection Agency's data host for air quality and are made publicly available.

Within the framework of international research networks, universities perform advanced measurements of various particle parameters at stations in regional background. An example of this is the ACTRIS network. This research contributes to improving understanding of particle properties, helps us to trace particles to their source and facilitates taking the right measures. Data from particle monitoring in Sweden are also used for research on health effects.

Access to data

A central part of monitoring is the processing of data. All national and municipal measurement results are reported annually to the EU and the Convention on Long-Range Transboundary Air Pollution and are used for international compilations and analyses. At national level, it is important to ensure data is easily accessible via the national air quality data host so that they can be used to evaluate environmental conditions and remedial efforts. For people who live in urban areas, it is particularly important to have access to up-to-date information on air quality. It is vital to prioritise improvements in data availability.

From research to legislation – and effects

Particles affect health regardless of the pollution level. It is therefore important to continuously strive towards lower levels to minimise adverse health effects as far as possible. Legislation is an important tool for driving improvements, and air quality is dependent on an ambitious regulatory framework based on the latest research findings. In September 2021, the WHO introduced new air quality guidelines, including tightened guideline values for PM_{10} and $PM_{2.5}$, and recommendations regarding ultrafine particles and soot. These new guidelines are based on extensive health studies, and it is crucial that they continue to be updated over time, not least within the EU where the Ambient Air Quality Directive is currently under revision. We have the tools at hand to lay a foundation that will lead to lower particle concentrations in Europe.

Text & contact:
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Further reading

National monitoring of particles in ambient air (naturvardsverket.se)

Nationell luftövervakning, IVL C 584 (diva-portal.org)

Swedish environmental quality standards for ambient air (naturvardsverket.se)

Luften i Sverige/Air Quality Sweden – charts with urban and regional background air quality data (naturvardsverket.se)

Swedish National Air Quality Data Host (smhi.se)

Swedish national research infrastructure - ACTRIS Sweden (actris.se)

Measuring particles – then and now

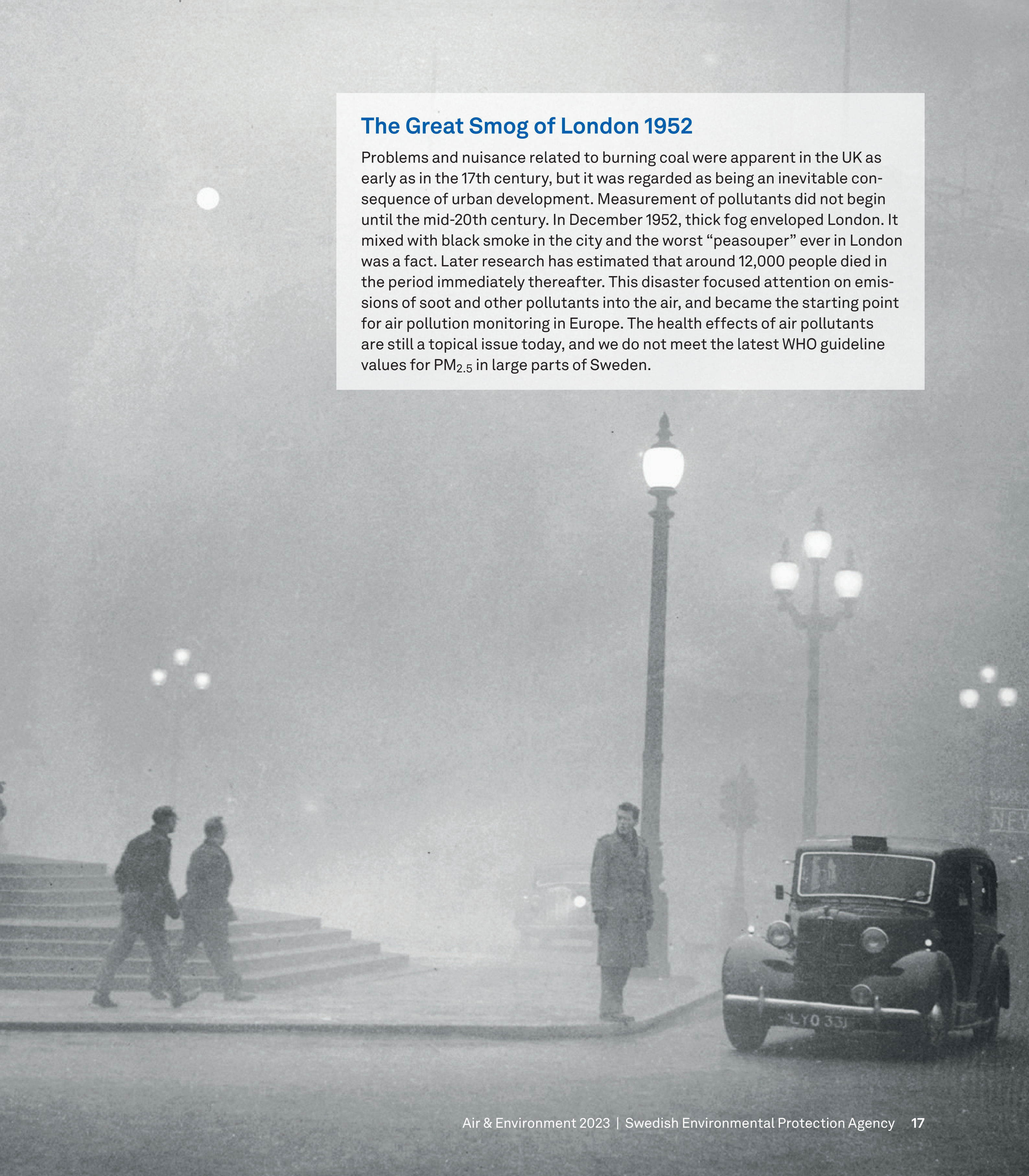
Odours, smoke and soiling from emissions of particles from energy production have long been a problem. Increasing industrialisation in the 19th century led to a significant increase in coal consumption and with it, higher emissions. International collaboration regarding both measurements and emissions reduction began when air pollutants were recognised as a major regional problem in the late 1960s.

The first air quality measurements in a Swedish urban area were performed in Gothenburg at the end of the 1950s. The experience gained from the Great smog in London (see fact box) gave reason to believe that the air in "Little London" (Gothenburg) could also have a significant health impact, as it also had signs of extensive smog formation.

The measurements revealed that the worst conditions occurred when there was a combination of poor air mixing, cold weather, fog and low wind speeds. Evaluation of the measurements found clear signs of long-range transport of pollutants. Many of the ideas from that period have been fundamental to the design of today's air quality monitoring strategies.

The Great Smog of London 1952

Problems and nuisance related to burning coal were apparent in the UK as early as in the 17th century, but it was regarded as being an inevitable consequence of urban development. Measurement of pollutants did not begin until the mid-20th century. In December 1952, thick fog enveloped London. It mixed with black smoke in the city and the worst "peasouper" ever in London was a fact. Later research has estimated that around 12,000 people died in the period immediately thereafter. This disaster focused attention on emissions of soot and other pollutants into the air, and became the starting point for air pollution monitoring in Europe. The health effects of air pollutants are still a topical issue today, and we do not meet the latest WHO guideline values for $PM_{2.5}$ in large parts of Sweden.



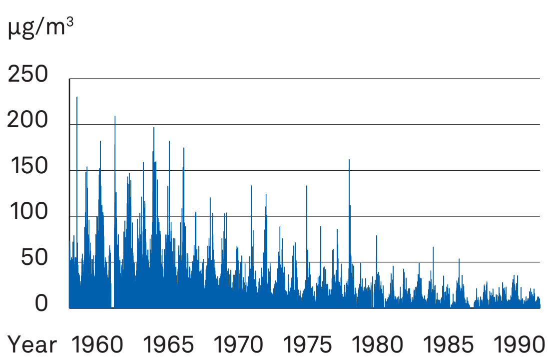
Trends since measurements began

Increased environmental regulations have reduced emissions from industry and energy production, both in Sweden and in Europe, which has generally led to a sharp reduction in the level of pollution in ambient air over the last few decades.

Soot concentrations in the air in central Gothenburg decreased by over 80 per cent from the beginning of the 1960s to the beginning of the 1990s. A similar trend can be seen throughout Sweden, both in urban and in regional backgrounds. Initially measurements in urban areas were mainly carried out in urban background locations (e.g. parks and squares) during the winter months. At the beginning of the 2000s, monitoring of the particle fraction PM_{10} largely replaced soot monitoring. In connection with having to meet the environmental quality standard for PM_{10} by 1 January 2005, more municipalities began measuring PM_{10}, mainly in street canyons in and throughout the calendar year, in accordance with the requirements of the air quality ordinance.

Figure 1. Soot levels in Gothenburg 1960–1993

In 1960, measurements in Gothenburg's city centre showed a few days with soot levels over 200 µg/m³.



Source: Swedish national air quality data host (SMHI).

Though lower, particle concentrations still exceed EQS and environmental objectives

A long-term reduction in particle concentrations can be seen in most urban areas with measurements over several years. The longest measurement series for PM_{10} in urban areas are from Stockholm, Gothenburg and Malmö. Results from these measurements show a clear decrease over the last two to three decades in concentrations. However, annual variations can be quite large, and the environmental quality standard for 24-hour means and the environment quality objective is still exceeded every year in several of the country's urban areas. A clearly decreasing trend has been observed in regional background at Aspvreten (Södermanland), the station at which background measurements of PM_{10} have been conducted for the longest time.

There are relatively few measurement stations for $PM_{2.5}$, due to generally low concentrations and subsequently lower measurement requirements. The longest measurement series are in Stockholm, Gothenburg, Malmö and Umeå, and these show a slight decreasing trend. The environmental quality objective is often met even in the most polluted areas. Since the early 2000s, rural areas have also shown a tendency towards decreasing concentrations.

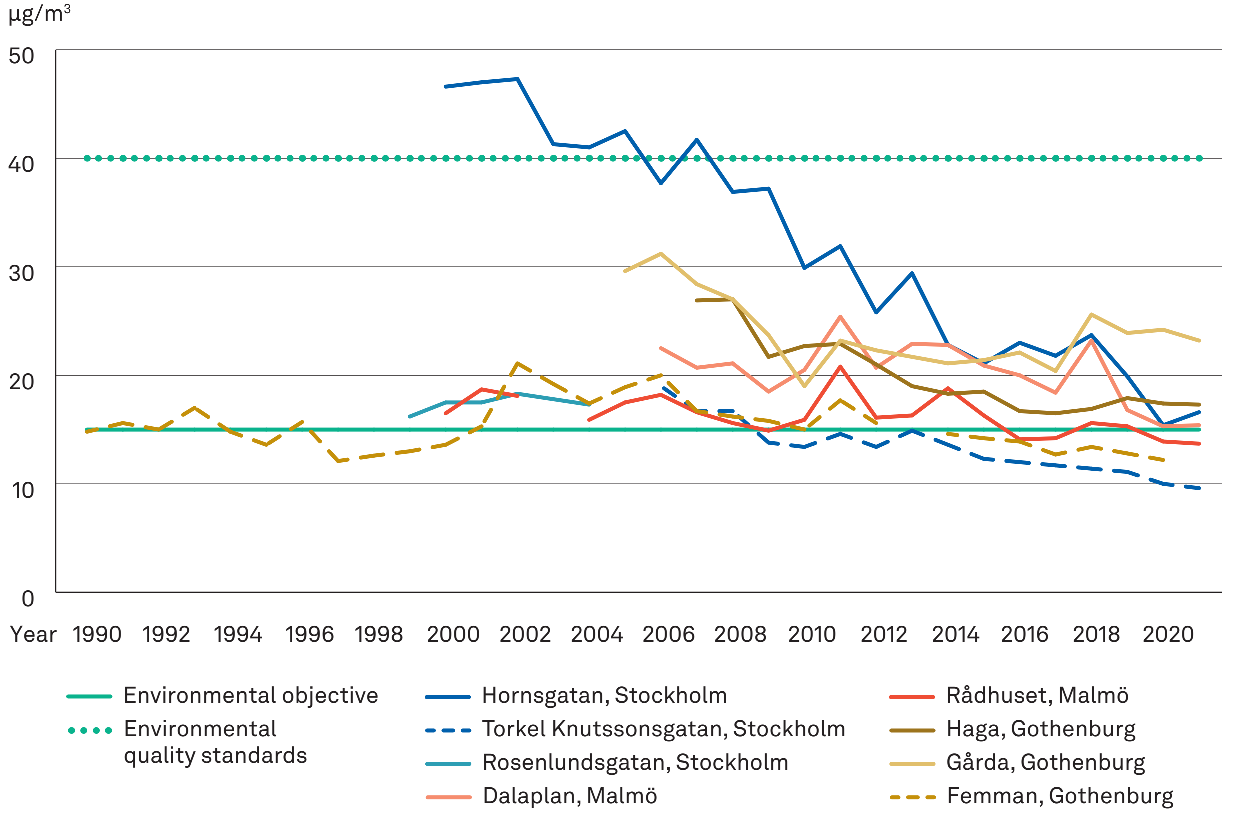
Shift of focus to particle sources and their importance

Particle concentrations have decreased significantly in most of Europe in recent decades, including in Scandinavia. This has been achieved mainly thanks to implementing modern technology, in industry and the transport and energy sectors with the introduction of stringent emission requirements. However, $PM_{2.5}$ emissions from housing and other buildings still present major challenges, particularly at European level. Road, tyre and brake wear is the dominant source of PM_{10} in Sweden, while European emissions of PM_{10} mainly come from housing and other buildings.

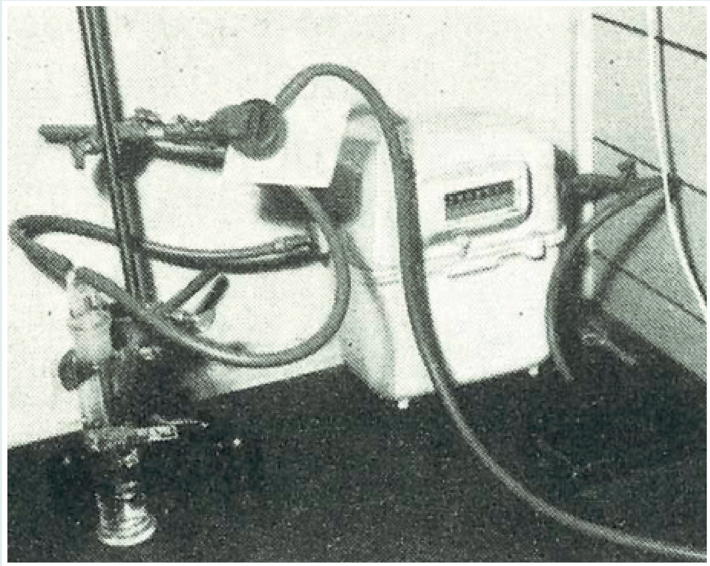
With the low concentrations of $PM_{2.5}$ in rural Scandinavia today, the significance of natural aerosol sources and processes is increasing. Sweden's natural ecosystem is dominated by forests, and the size of the forests in cubic metres of wood biomass has doubled over the last hundred years. Forests are an important natural particle source because trees emit volatile organic compounds (VOCs) that can form particles through chemical conversion into the atmosphere. As the climate changes over time with expected temperature rises, emissions of VOC and related levels of particulate matter will increase. This effect is reinforced by an increased risk of forest fires,

Figure 2. Annual mean PM_{10} in street canyon and urban background locations 1990–2021, micrograms per cubic metre

Trends in PM_{10} concentrations in Gothenburg urban background and street canyons (the Femman measurement station and Haga and Gårda stations), Stockholm in urban background (Rosenlundsgatan/Torkel Knutssongatan station) and at street canyon (Hornsgatan station) and Malmö in urban background (Rådhuset station) and at street canyon (Dalaplan station).



Source: Swedish national air quality data host (SMHI).



Evolution of measurement methods

During the 1960s and 1970s, particles were mainly measured in Sweden by measuring the reflectance from blackening of a white paper filter caused by separated particles. The method gives a rough measure of the presence of black particles (soot, <3–5 micrometres).

The principle of the current reference method for monitoring particulate matter concentrations under the EU Air Quality Directive is based on the same sampling idea. The air is sucked in through a specially designed inlet that separates particles of specific sizes (for example $PM_{2.5}$ or PM_{10}). The mass of these particles is determined by weighing the filter before and after sampling.

The most common continuous measurement methods in Swedish environmental monitoring today are hourly measurements using light to count and determine the size of particles. The instruments then convert these measurement data into mass concentrations, such as PM_{10} and $PM_{2.5}$. These instruments are approved as equivalent to the reference method.

which are expected to become more common and more intensive in a warmer climate.

Particles in urban environments have gone from being a visible and significant threat to health to no longer being visible. However, the health risks remain and are becoming clearer as more research is conducted. Particles have also become central within climate research over time, as their complex role in the climate system is not yet fully understood and they represent one of the greatest uncertainties in our ability to predict future climate change.

What particle measurements can we expect in the future?

Because particle concentrations have decreased in recent years, formal requirements for monitoring have also decreased. However, there is increasing evidence of negative effects of particles on health, even at low concentrations, so measurements will continue to be needed. WHO updated its air quality guidelines in September 2021, and the guidelines regarding particles are now considerably stricter and more comprehensive. When the revised EU Air Quality Directive is adopted, it is likely that it will make environmental quality standards for air quality stricter, leading in turn to further requirements for monitoring particles. The focus will likely also be extended to other particle sizes and sources, such as ultrafine particles and soot (BC), as further research identifies the effects of increasingly smaller particles. Modelling of particle concentrations will also likely gain in importance.

Measurement methods continue to evolve

Measuring particle concentrations is costly. This limits how extensively measurements can be performed and who can perform them. In the future, however, we will likely see a shift toward the use of simpler and cheaper sensors for both gases and particles. Such sensors can be placed throughout a city to gain a better picture of how concentrations vary in different urban environments. Many questions remain about the quality of the data produced by these sensors, but it is possible that we will eventually have sensors integrated into our mobile phones and be able to receive alerts if we are in an area with significant air pollution. This would allow asthmatics and others sensitive to pollution to avoid unhealthy situations. Data from a variety of mobile sensors could also be digitally transmitted and compared in real time to urban dispersal models. Such a system would help residents better understand the problem of air pollution and would strengthen transparency around clean air issues.

International research collaboration on particle measurements

Particles are a large-scale problem that affects both human health and the climate. That makes international long-term cooperation crucial. Across Europe, researchers perform particle measurements within the framework of ACTRIS (www.actris.eu), a European infrastructure for the monitoring of aerosols, clouds and trace gases.

The Swedish part of the ACTRIS infrastructure has received funding from the Swedish Research Council for the period 2022–2026, and ACTRIS-Sweden will develop five stations for several different types of particle measurements (e.g. particle numbers, size distribution, light scattering and absorption, and chemical composition). In addition, organic gases, sulphur and nitrogen oxides will be monitored. ACTRIS-Sweden will contribute to Sweden's environmental monitoring of airborne particles and make more data available to modellers, municipalities and the general public.

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Further reading

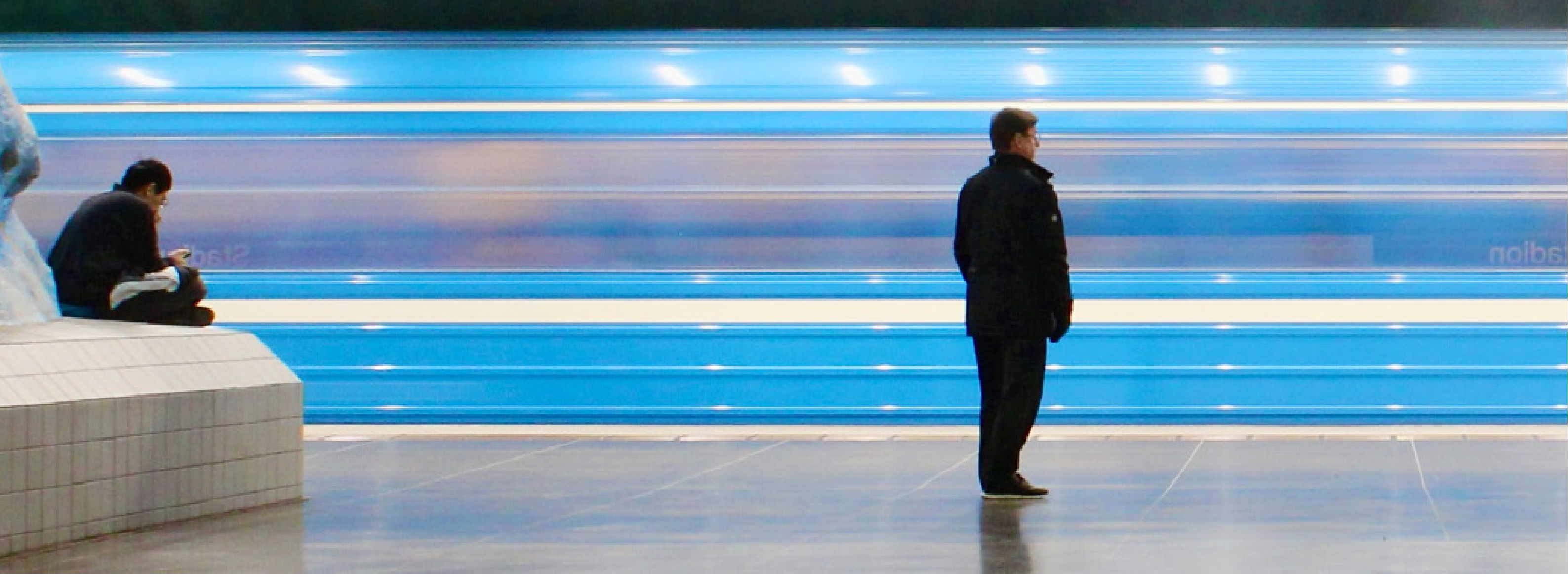
Air startpage (naturvardsverket.se)

Air quality in Europe 2022 (europa.eu)

Air Quality Ordinance (2010:477) (riksdagen.se)

Tillbakablick över luftkvalitetsmätningar i svenska tätorter, IVL B1574 (ivl.se)

Urbanmätnätet – 30 års mätningar av luftkvalitet, IVL Swedish Environmental Research Institute C230 (ivl.se)



Ultrafine particles – invisible but everywhere

The smallest particles are called ultrafine particles (UFP). By number they make up the majority of particles in air and can penetrate the deepest into the lungs before becoming lodged there. They can also act as carriers of toxic substances and can enter the bloodstream. Vehicle exhaust is the most important source of exposure to ultrafine particles. This is why there are requirements for maximum emissions from new cars, but there are still no regulations that limit concentrations in the air.

There is no precise definition of the size of ultrafine particles, but particles smaller than 100 nanometres are commonly considered ultrafine. Therefore, concentrations include the smallest nanoparticles and are reported as the total number of particles per cubic centimetre ($1/cm^3$), unlike PM_{10} and $PM_{2.5}$ which is the total mass (weight) per cubic metre.

Why ultrafine particles are important

UFP are measured using different types of particle counters (see fact box). Some particle counters can count particles down to 2 nanometres, while others only count particles that are larger than 7 nanometres or 10 nanometres. This may sound like small differences when the particles differ only a few nanometres in size, but it can significantly affect the number of particles detected, especially when the measurement takes place in a traffic setting where there may be large amounts of the smallest particles.

Because the ultrafine particles are so small, their mass is a very small part of PM_{10} and $PM_{2.5}$. From a health perspective, however, their measurement is particularly important because the smallest

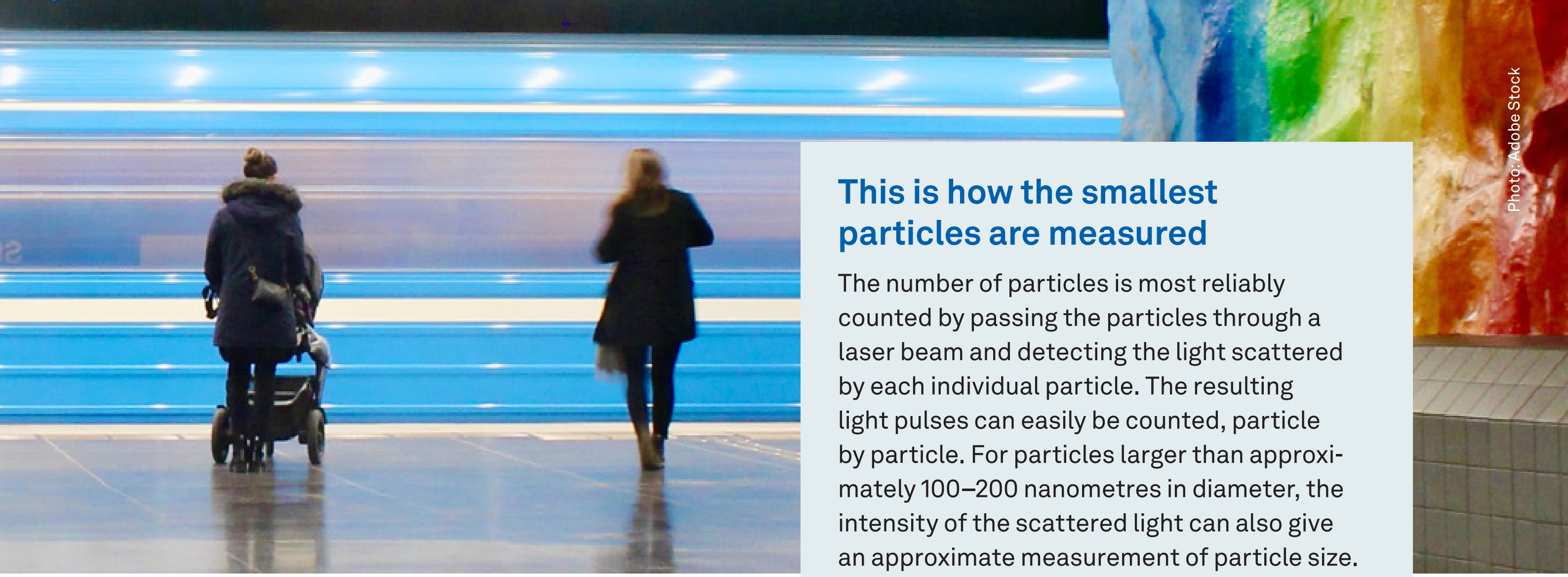


Photo: Adobe Stock

This is how the smallest particles are measured

The number of particles is most reliably counted by passing the particles through a laser beam and detecting the light scattered by each individual particle. The resulting light pulses can easily be counted, particle by particle. For particles larger than approximately 100–200 nanometres in diameter, the intensity of the scattered light can also give an approximate measurement of particle size. These instruments are often referred to as optical particle counters and are also used to measure PM concentrations. For the smaller, ultrafine particles, the particle has to grow in size before crossing the laser beam. This is ensured by allowing the particles to form droplets with butanol, isopropanol or water. Such instruments are often referred to as CPCs (Condensation Particle Counters).

The size distribution of the smallest particles is measured by first sorting the particles by size. The number of particles in each size range is then calculated. The sorting is normally done by charging the particles electrically before they are classified in a strong electrical field. The diameter by which particles are sorted is called the electrical mobility diameter. The instruments that do this can have different names, DMPS: Differential Mobility Particle Sizer, SMPS: Scanning Mobility Particle Sizer, or MPSS: Mobility Particle Size Spectrometer.

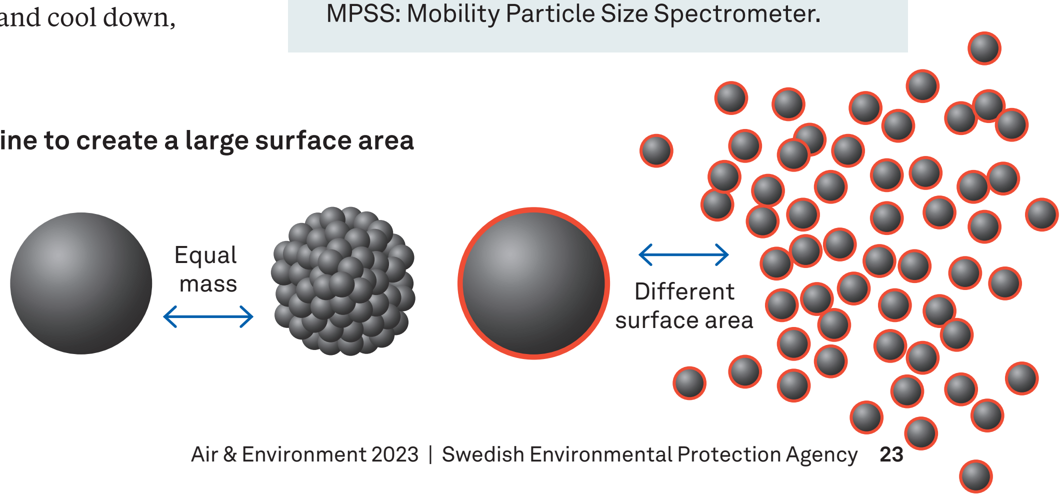
nano-sized particles have a large (potentially reactive) surface in relation to their mass (see Figure 1) and can penetrate deeper into the lungs (alveoli), stay longer in the body and even enter cells and the bloodstream. In this way, like Trojan horses, they can transport toxic substances into the body (e.g. polycyclic aromatic hydrocarbons, PAH).

Where do ultrafine particles come from?

Road traffic is the main source of UFP in cities. They are mainly formed by incomplete combustion and are largely made up of hydrocarbons, soot and sulphate compounds. Older diesel vehicles without particle filters account for the largest contribution to UFP in cities. UFP can also be formed in the air when exhaust gases are diluted and cool down, known as secondary particles.

Figure 1. Small particles combine to create a large surface area

Multiple small particles that together form the same mass as a single particle have a larger surface area than the single, large particle. This means that they have a large area that can react with their surroundings.



Another source from road traffic is mechanical wear of brakes and studded tyres, which can form ultrafine particles consisting of metal and metal oxides. This has been demonstrated in laboratory settings, but it is likely that these emissions have very little impact on the presence of UFP in ambient air. As vehicle fleets become more electrified, the proportion of mechanical wear will increase as emissions from vehicle exhaust disappear.

Other sources include non-road mobile machinery and ships, wood-burning stoves, residential boilers, large-scale boilers and large energy plants. In general, emissions from these sources do not contribute as much as road traffic to the population's exposure. However, in residential areas with heavy use of wood for heating and in port areas, the importance of these emissions increases.

WHO recommends measuring particle numbers

As there are no limit values for the presence of UFP in the air, there has been very little measurement of their concentrations in urban air. However, WHO's latest global air quality guidelines from 2021 recommend measurement of particle numbers. Furthermore, they recommend distinguishing between low and high levels. Low levels are mean concentrations over 24 hours of less than 1,000 particles per cubic centimetre. High levels are defined as above 10,000 per cubic centimetre over 24 hours or an average of 20,000 per cubic centimetre over one hour.

Emission control rules

Newly registered vehicles or vehicles that enter into service in the EU must meet certain emission requirements, including the mass and number of particles in their exhaust emissions. The rules for particulate mass emissions from diesel cars were first introduced in 1992 (Euro 1). The rules for particle number were first introduced for diesel cars in 2011 (Euro 5b) and a few years later also for petrol cars with direct injection (Euro 6) and heavy vehicles and non-road mobile machinery. Emission regulations apply only to particles with a diameter greater than 23 nanometres.

A particle filter effectively cleans exhaust emissions of particulate matter. Emissions are 10,000 times lower with particle

Photo: Adobe Stock

Road traffic is the largest source of emissions of ultrafine particles. Other sources include non-road mobile machinery, ships and wood-burning stoves.

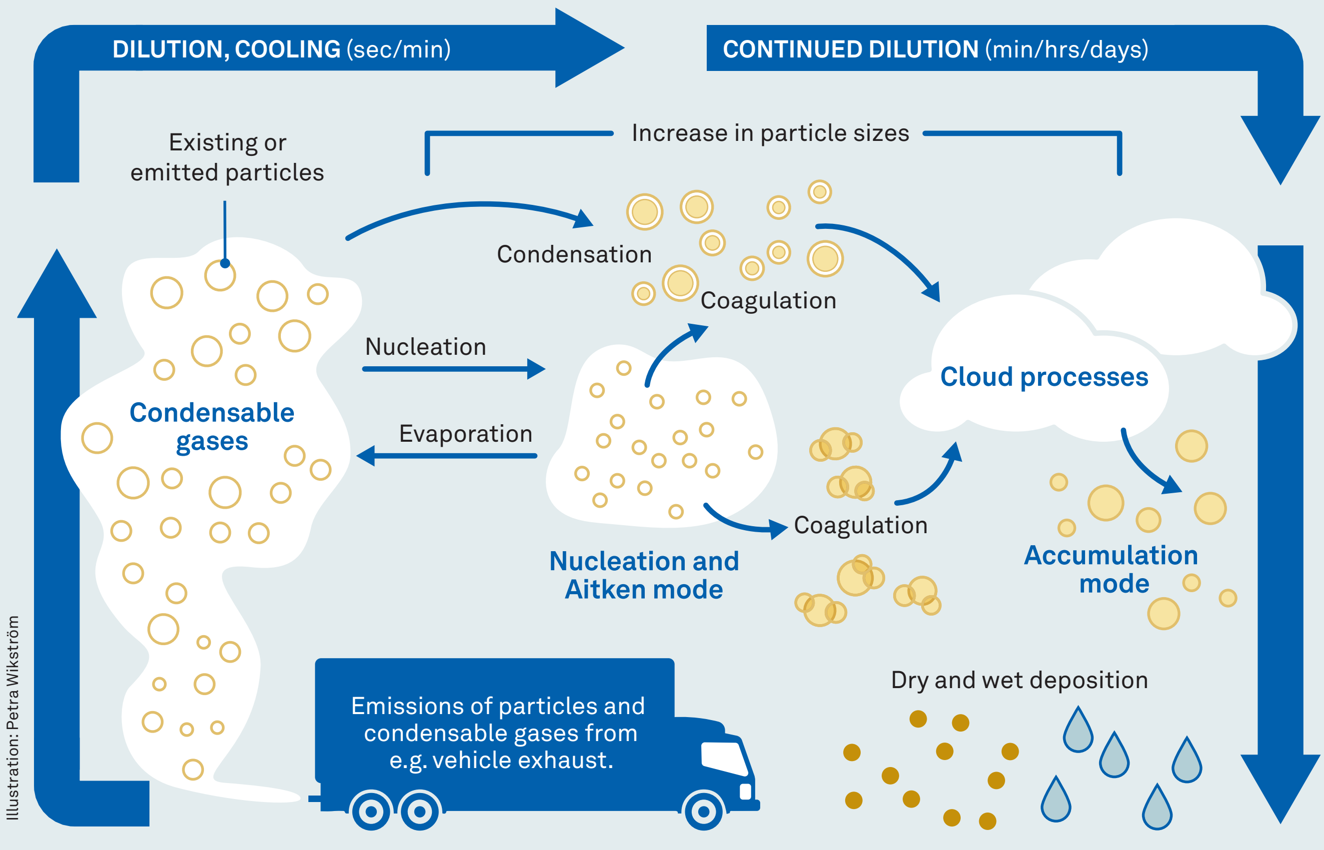
filters than without. However, gaseous substances, such as volatile hydrocarbons, that can pass through the filters may cause the formation of nanoparticles as the exhaust gases are diluted and cooled when the exhaust is mixed with the ambient air (see Figure 2). There may be large numbers of particles less than 23 nanometres in ambient air, especially near busy roads.

UFP are formed in the air after emissions

Figure 3 illustrates the entire life cycle of ultra-fine particles, from primary emissions and the formation of UFP in the air to the final deposition on the ground. The processes in the air, combined with the size of the particles emitted, give rise to particles of different sizes.

Figure 2. Illustration of the processes in the lifecycle of ultrafine particles

Illustration of the processes that affect airborne particles after their emission. Nucleation means that new particles are formed, the condensation of gases on the particles increases their size, and coagulation means that several particles merge into one, reducing the number of particles. Chemical reactions occur in cloud drops that affect the composition and size of particles.



Source: Air Quality Expert Group: Ultrafine particles (UFP) in the UK.

Exhaust emissions from road traffic contain both solid particles and droplets. Exhaust gases are diluted and cooled immediately after their emission from the tailpipe. This results in hydrocarbons being condensed mainly on existing particles, resulting in larger particles. It can also cause new particles to form if there are too few particles to condense upon.

When measuring particle size distributions in ambient air, particles can be divided into different ranges or “size modes”. Many of the particles that are larger than 100 nanometres (accumulation mode) have reached that size after passing through one or more clouds, where they grow in size as gases dissolve in the cloud droplets and form solid or liquid compounds, including sulphates and nitrates.

Locations with high ultrafine particle levels

The concentration of UFP in the atmosphere can vary from 100 to over one million particles per cubic centimetre, depending on the proximity to emission sources. The highest levels of UFP to which people are regularly exposed are measured on busy streets in big cities, where there can be tens of thousands of particles per cubic centimetre (measured as an hourly mean value). In Stockholm, the urban background level is between 5,000 and 10,000 particles per cubic centimetre. Closer to traffic it is more or less double this. In rural areas, far outside the cities, the concentration is just over 1,000 particles per cubic centimetre.

Concentrations of ultrafine particles in different settings are shown in Figure 3. The relative differences in UFP concentrations in these settings are significantly higher than if PM_{10} or $PM_{2.5}$ are used as particle measurements. Concentrations of PM_{10} in subway systems may be up to ten times higher than in street settings, while UFP levels are significantly lower in subways than in the street settings, due to differences in the sources of the particles. Similarly, the relative differences in concentrations in different places within a city are significantly greater for UFP compared with PM_{10}, because local sources have a greater impact on UFP than PM_{10}.

Figure 3.

Comparisons between the concentration of particles per cubic centimetre and PM_{10} particles per cubic metre in different settings.

Photo: Stockholm Image Bank

Busy street
UFP: ~10,000/cm³ PM_{10}: ~20 µg/m³

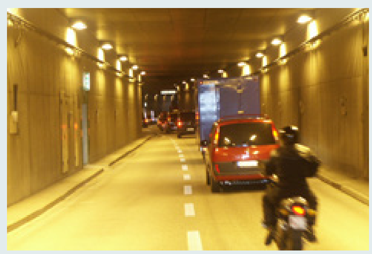


Photo: Stockholm Air & Noise Analysis

Road tunnel
UFP: ~100,000/cm³ PM_{10}: ~250 µg/m³

Photo: KTH

Subway
UFP: ~5,000/cm³ PM_{10}: ~200 µg/m³

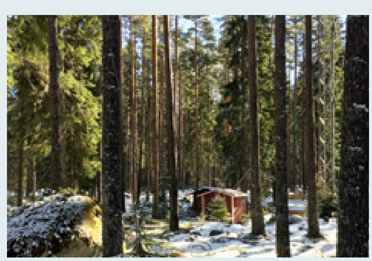


Photo: Stockholm University

Forests
UFP: ~2,000/cm³ PM_{10}: ~6 µg/m³

Trends are heading in the right direction

At present, UFP has only been measured continuously in a few places in Sweden. Long-term measurements of the number of particles at street level and roof

Figure 4. Ultrafine particles on weekdays in Stockholm

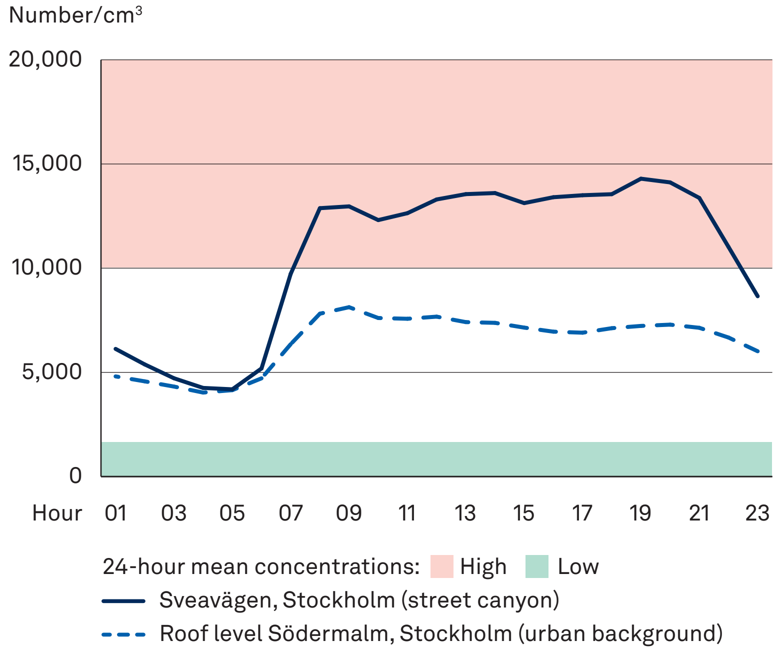
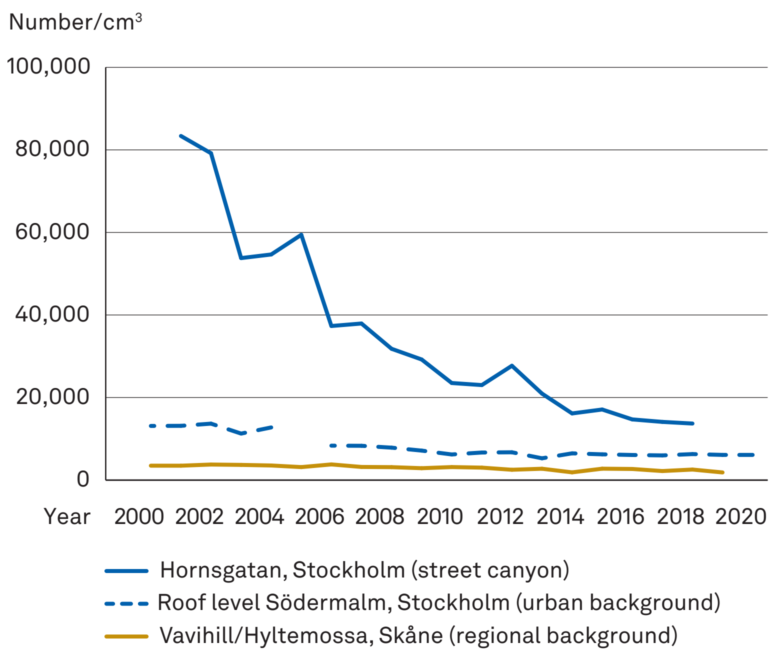


Figure 5. Trends for ultrafine particles in Sweden 2001–2021



level in Stockholm and in rural areas in southern Sweden show that particle levels are decreasing. The levels at Hornsgatan in Stockholm decreased by more than 80 per cent between 2002 and 2019 (see Figure 5). In urban ambient air in central Stockholm, the decrease is just under 60 per cent and in rural areas of Skåne around 20 per cent. The sharp decrease in Hornsgatan reflects the reduction in emissions of exhaust particles resulting from cleaner vehicles. We have seen a great improvement in concentrations but have some way to go before WHO's recommended levels are achieved.

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Further reading

Kumar, P. et al (2010). A review of the characteristics of nanoparticles in the urban atmosphere and the prospects for developing regulatory controls (sciencedirect.com)

New WHO Global Air Quality Guidelines (who.int)

Black Carbon – the black sheep of air

Incomplete combustion produces soot particles that are likely to be harmful to health when inhaled. They also affect the climate by absorbing solar radiation. Studies have shown that soot particles are one of the most important groups of air pollutants related to adverse effects on human health. That is why the WHO recommends regular monitoring and actions that can reduce concentrations.

What is soot?

Soot is a collective term for carbon-containing particles resulting from incomplete combustion. The classification given depends on the measurement method used to determine soot concentrations.

Black smoke (BS) was previously measured by the reflectance of white light from a filter with collected particles that was then recalculated using an index. However, because the optical properties of particles vary and particles other than soot can have an effect, comparisons with BS must be taken with a pinch of salt.

Black carbon (BC) or equivalent black carbon (eBC) is measured by the absorption of light at one or more wavelengths. Subsequently, the measured absorption is converted to mass.

Elemental carbon (EC) provides soot concentrations using a method in which a filter sample is heated gradually and then vaporised and burned.

Refractory black carbon (rBC) gives soot concentrations by using a strong laser to heat soot particles until they produce light. These signals can be converted into a mass of soot particles.

Small particles can penetrate further into the lungs, impacting vascular, cardiac and respiratory health and causing lung cancer. Levels of airborne particles have decreased significantly in recent years, while knowledge of their harmful effects has grown. It is most common to measure particle concentrations as PM_{10} and $PM_{2.5}$, although smaller particles, including soot particles, could cause greater injury. The new WHO air quality guidelines from 2021 include recommendations for systematic soot measurements and for reducing concentrations further.

The effects of soot particles have long been known

Soot particle levels have been measured for a long time in both urban and rural areas – well before measurements of PM_{10} and $PM_{2.5}$. The first documented measurements in Europe are from the 1920s. Most quoted are the extremely high concentrations in London during the Great Smog in December 1952. That event had particle concentrations with a large percentage of soot particles of up to 4,000 micrograms per cubic metre. This is up to 1,000 times higher than the worst episodes in Sweden today. It is estimated that the Great Smog episode and the time shortly thereafter caused 12,000 premature deaths.

In Sweden, measurement of soot particles began in Gothenburg at the end of 1950 and a few years later also in other municipalities. The suspicion that soot not only came from emissions from Swedish cities but could also be transported in from other countries was later confirmed by measurements made at several lighthouses along the Swedish coast (Sandhammaren, Falsterbo, Nidingen, etc.).

Photo: TT

Hornsgatan in Stockholm is one of Sweden's busiest streets. In a busy urban environment, up to 30 per cent of the particles can contain a core of soot.

How soot is formed

Soot is produced by incomplete combustion of fuels containing hydrocarbons. The formation of soot particles also requires combustion under oxygen-deficient conditions. Under these conditions, combustion forms layers of graphene that bend around a core like the layers of an onion. When the "onion" is complete, it has grown to 10–30 nanometres in diameter and is a primary soot particle. These small particles quickly merge to form larger fluffy aggregates that can consist of several hundred primary soot particles of sizes 100–200 nanometres. These are the soot particles that we find in the air.

The soot particles then "mature" in the atmosphere through condensation of organic matter, sulphur and nitrate or are absorbed as soot agglomerates, forming particles of a mixed chemical composition. After several hours, particles become more spherical. Soot particles can be transported by air to reach even remote locations, far from the original source.

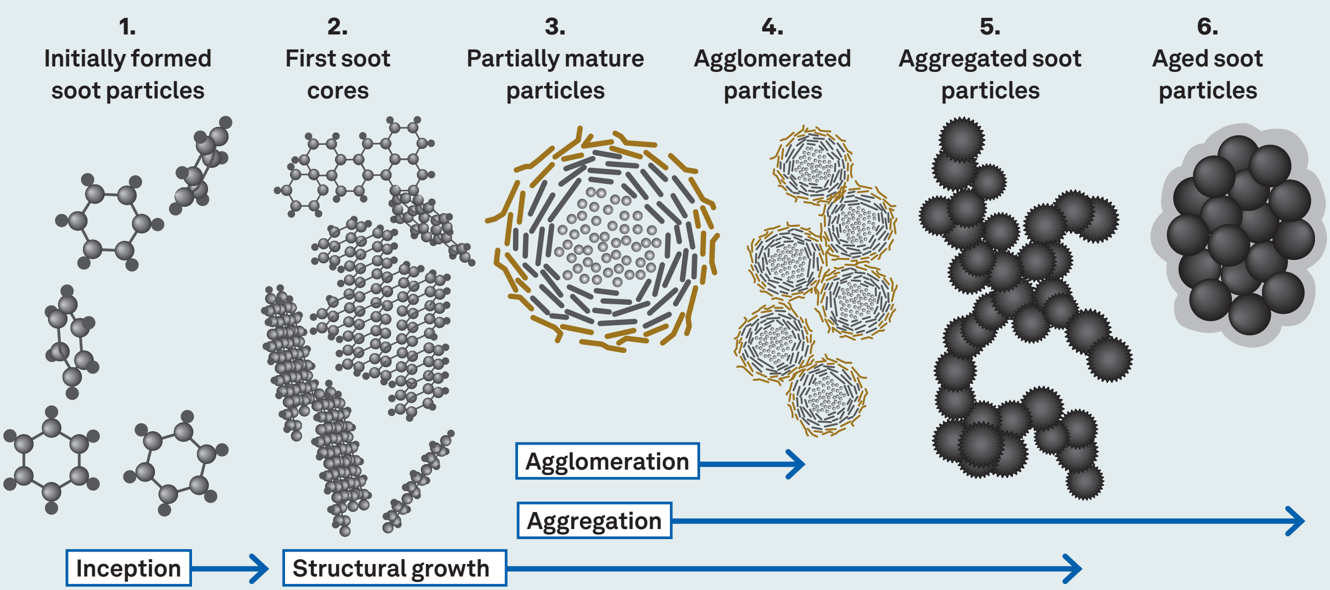
About every twentieth particle in ambient air in southern Sweden contains a soot core. In a busy urban street setting, this number is a bit higher, around 10–30 per cent of the total number of particles.

Greatly reduced soot concentrations in Sweden

Very high soot concentrations were measured in Gothenburg and Stockholm during the winter months in the 1960s. Since 1965, concentrations have fallen by around 97 per cent. Similar trends in soot concentrations have also been seen in several other Swedish cities. The most important reason for the reduction in concentrations in the 1970s and 1980s was the major expansion of district

Figure 1. Formation of soot particles

Soot particles are formed in the flame during combustion and the particles then mature in the air.



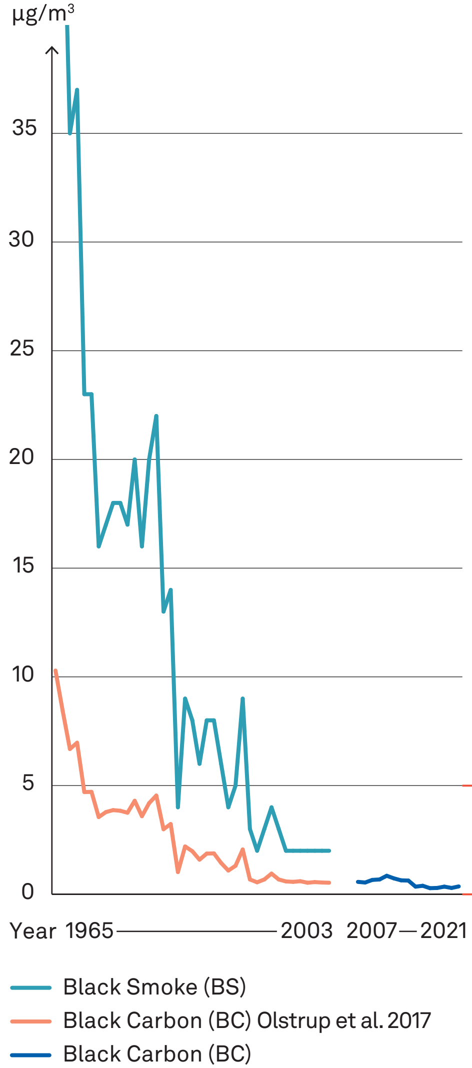
Source: Redrawn from Michelsen, Hope A. et al. ACS Nano 2020, 14, 10, 12470–12490.

heating, with reduced emissions from oil-fired boilers in urban areas. In the last 10 to 20 years, the reduction in particle emissions from car traffic has also contributed to a decrease in soot particle concentrations. Currently (2022), soot particle concentrations are measured in Malmö, Stockholm and Umeå (see Figure 2).

Knowing the origin of soot particles makes work on mitigation more efficient

Soot absorbs visible light, but soot particles absorb light differently depending on their chemical composition. This applies especially to soot particles from traffic and wood-burning stoves, currently the two dominant

Figure 2a

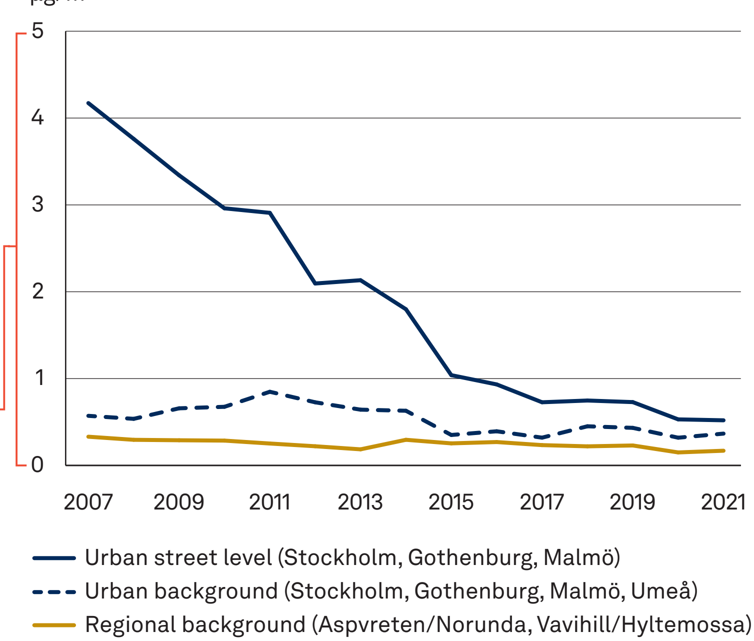


Soot concentrations in Sweden 1965-2021

Figure 2a. Stockholm roof level soot
Annual mean values of soot particulate concentration measured as black smoke (BS) and black carbon (BC) at roof level in Stockholm. For comparison, BS concentrations have also been converted to BC, based on Olstrup et al. (2017).

Figure 2b. Soot in Sweden
Annual mean values of soot particle concentrations measured as black carbon (BC) for regional background, urban background and at street level.

Figure 2b



sources of these particles in urban environments.

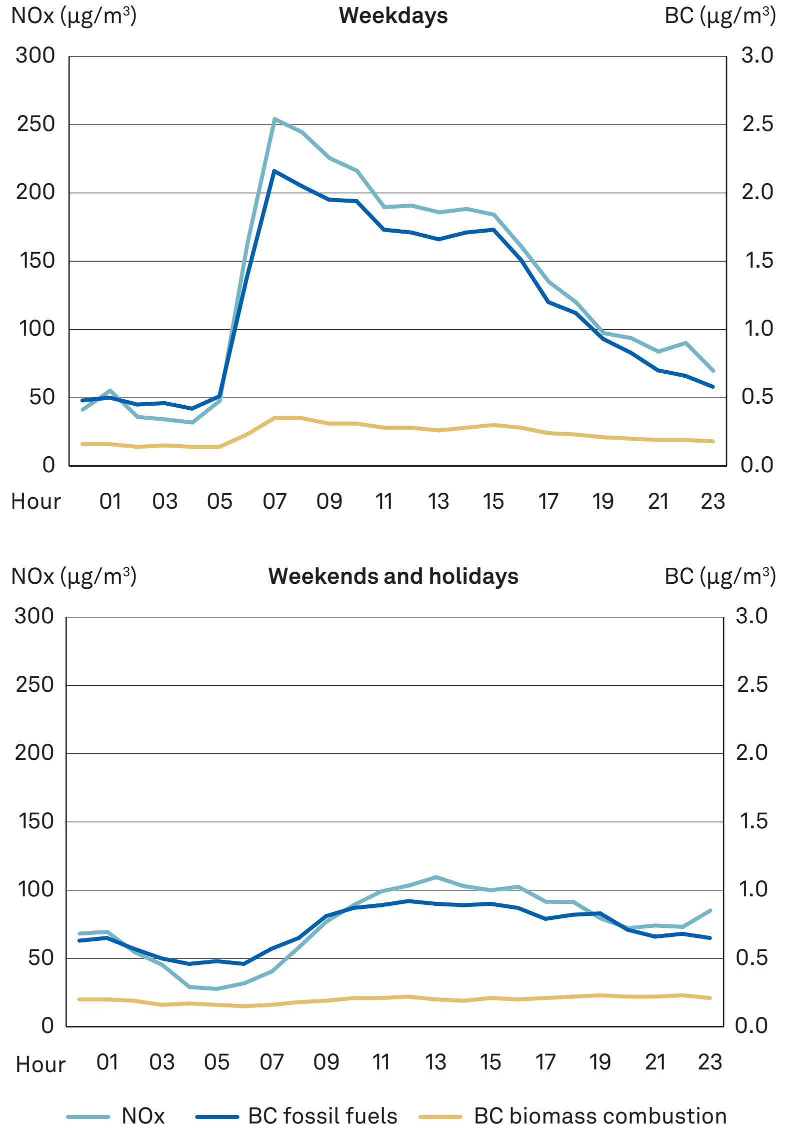
Soot from biomass combustion contains a high proportion of organic material, called brown carbon, which also absorbs light. The brown carbon absorbs blue light more effectively than red light, creating a wavelength dependence. The strength of the wavelength dependence is described by the Ångström wave exponent. Traffic-related soot particles contain a smaller proportion of organic material, which means that the particles are completely black and absorb with equal efficiency regardless of the light's wavelength.

There are currently several instruments that can be used to measure the absorption of soot particles. Several of these measure soot optically at different wavelengths. The instruments use the difference in light absorption for the various wavelengths to determine the dominant source of the soot that is measured at a specific location. The instruments measure the total absorption, both soot and brown carbon, which together are called Black Carbon (BC). This means that the ability of soot to absorb different colours may vary even though the amount of BC is constant.

By utilising the wavelength dependence of soot particles, we can determine the source of

Figure 3. The daily variation of soot particles and their link to traffic exhaust

The figure shows the source apportionment of soot particles from traffic and biomass combustion on weekdays (upper picture) and at weekends (lower picture) at a very busy monitoring site (Hornsgatan, Stockholm). This is done by comparing the level of nitrogen oxides (NOx), since these are mainly from traffic and correlate well with fossil soot.



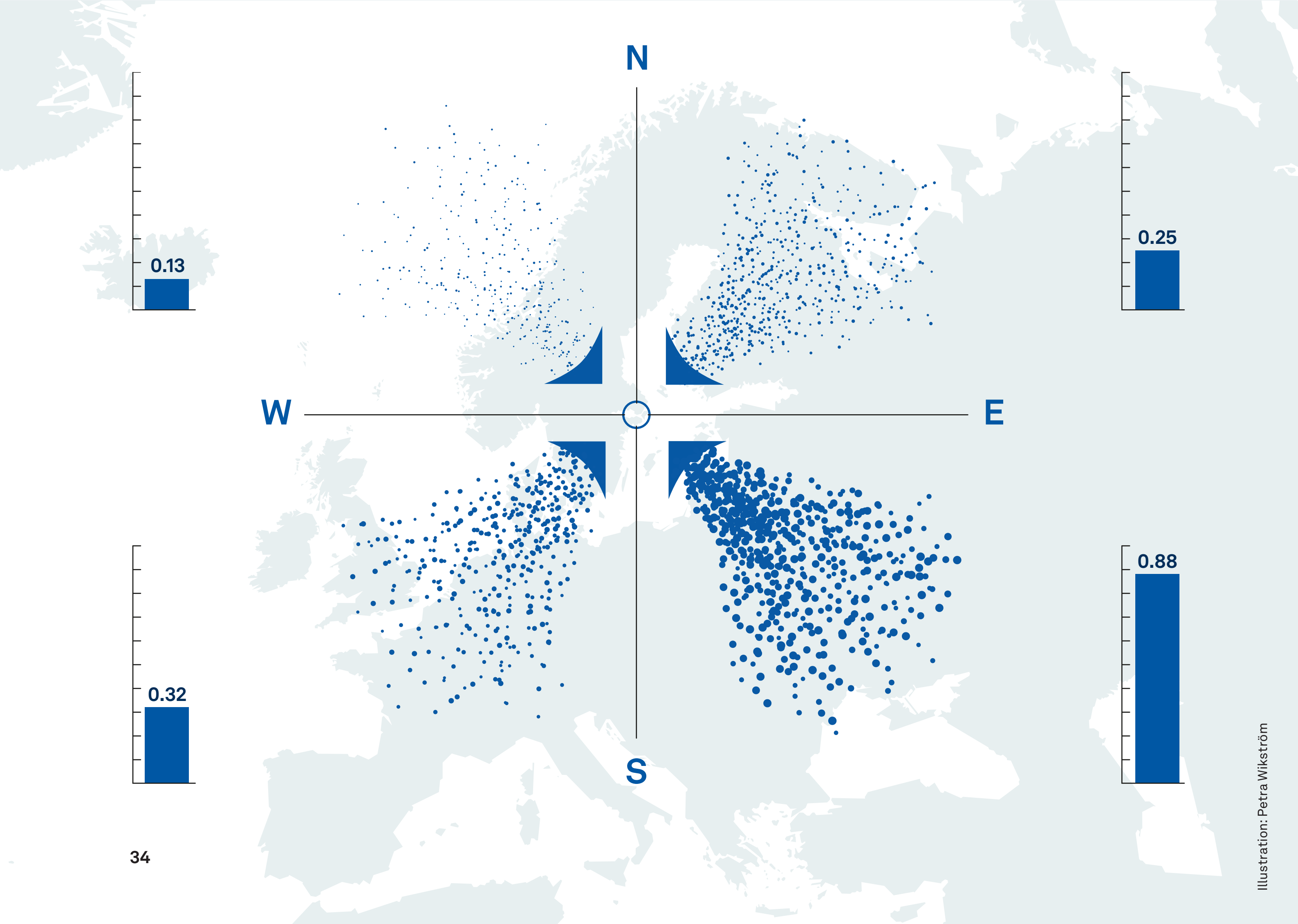
measured soot particles and more efficiently mitigate the problem. Once we know where the soot comes from, mitigation measures can be directed at the right source. Clearly indicating where different measures would be most useful is important when decision-makers require a justification to act.

A significant and increasing percentage of carbon content is due to transport from other countries. Figure 4 shows that the highest concentrations of BC are observed when the air is transported from south-east and the lowest concentrations when the air comes from the north-west.

Figure 4. Long-range transport of soot is very significant

Average BC concentrations at Aspvreten (outside Nyköping) in air from different geographical sectors. Based on measurements 2005–2010.

Source: Redrawn from Jönsson et al., Air pollution episodes in Stockholm regional background air due to sources in Europe and their effects on human population. Boreal Environment Research, 18, 280–302.



Measures and cooperation to reduce soot levels

Important measures in the reduction of BC emissions include reducing diesel road transport and reducing the use of wood in domestic heating or taking measures to improve the efficiency of the use of wood as fuel. The pace of adoption of electric vehicles has had a major impact on how fast BC emissions are decreasing, but the addition of renewable fuels to diesel fuel also reduces emissions, and particle filters in new cars remove more than 90 per cent of particles.

There are currently no environmental quality standards or specified environmental quality objectives for soot. However, reducing emissions is important to reduce the health effects, climate effects and soiling effects of soot. The Gothenburg protocol (under the UN Convention on Long-range Transboundary Air Pollution) and the EU National Emission Ceilings Directive identify soot as the most important part of particulate emissions for reduction, and emissions are already being reported by several countries. Reported data is an important foundation for understanding emissions, sources and trends so that the right measures can be applied locally and globally. International collaboration is crucial for ensuring everyone breathes air of good quality since soot is dispersed across large areas.

Photo: Johnér

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Further reading

Soot emissions (naturvardsverket.se)

BMJ Open May 2022 - Volume 12 - 5 (bmjopen.bmj.com)

Nilsson Sommar, J. et al (2021). Long-term exposure to particulate air pollution and black carbon in relation to natural and causene-specific mortality: a multicohort study in Sweden (bmjopen.bmj.com)

Ljungman, P. et al (2019). Long-Term Exposure to Particulate Air Pollution, Black Carbon, and Their Source Components in Relation to Ischemic Heart Disease and Stroke | Environmental Health Perspectives | Vol. 127, No. 10 (nih.gov)

Photo: Adobe Stock

Small particles cause major health problems

Airborne particles cause significant levels of ill-health both globally and in Sweden. Research shows that particles contribute to a wide range of diseases and that certain sensitive groups should be given particular consideration. In recent years, adverse health effects have been linked to very low levels of particulate matter even below the Swedish environmental quality objectives.

We breathe in large amounts of airborne particles every day, and they cause both children and adults to suffer from a range of illnesses. It has long been known that particles increase the risk of cardiovascular disease and premature death. It is becoming increasingly clear that they also have an impact on foetal development, increase the risk of type 2 diabetes and various forms of cancer, affect brain functions and increase the risk of dementia. Particles have both fast and slow acute and chronic effects on the body. The risk of asthma attacks or heart attacks increases within a few hours or days of exposure, while years of exposure can contribute to cancer, atherosclerosis or reduced lung function.

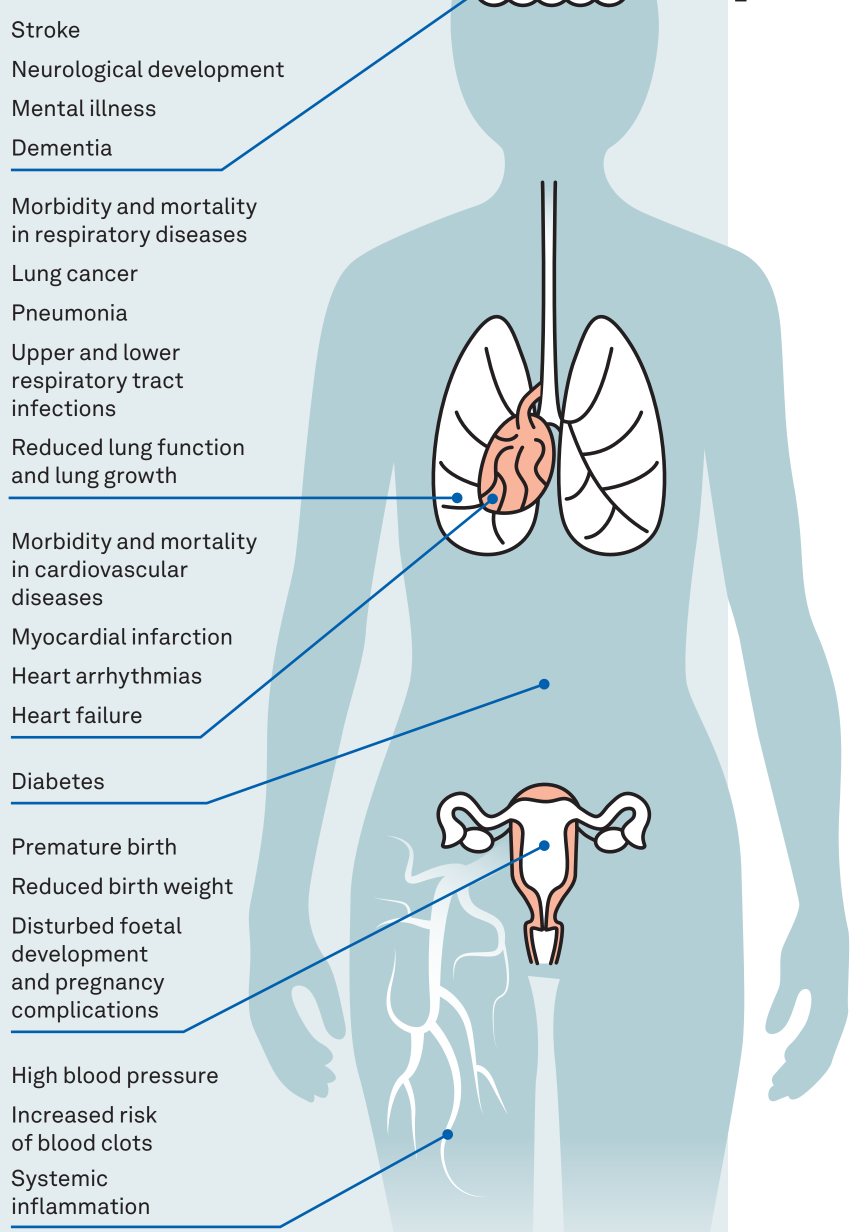
Airborne particles affect the whole body

Particles that have been inhaled can penetrate deep into the lungs and in some cases also pass through the bloodstream to the liver, brain and kidneys. There are several different ways in which particles can contribute to disease. The risk of inflammation and oxidative stress (damage caused by reactive oxygen species) increases as does the impact on the autonomic nervous system. There are also signs that particles can affect the ability of blood vessels to increase blood flow in the event of oxygen deficiency and affect the blood's clotting ability.

Individuals with underlying diseases, such as heart or lung diseases, are more at risk than healthy individuals to air pollutants like particles. Pregnant

Figure 1. Diseases linked to air pollutants

Summary of diseases linked to particulate air pollutants.



Source: Based on Thurston, G.D. et al. (2017).

Illustration: Petra Wikström


Photo: Adobe Stock

Children are particularly sensitive to air pollutants, both because they are growing and because they spend a lot of time outdoors. Individuals with underlying diseases can also be more sensitive than healthy individuals.

women are also considered to be particularly at risk, because foetuses can be affected by particulate air pollution during pregnancy. The same applies to young children, because their small and growing airways are more sensitive and they spend a lot of time outdoors. Children's health in relation to the air and environment has been described in detail in a previous report from the Swedish EPA, "Air & Environment – Children's Health" from 2017.

There is no safe lower limit

In recent years, adverse health effects have been linked to ever lower levels of air pollutants, even at levels below the current Swedish environmental quality objectives. The Swedish Clean Air and Climate Research Program (SCAC), with participants in Gothenburg, Stockholm and Umeå, identified the connection between air pollutants in homes and the risk of both stroke and premature death. In international comparisons, the levels of air pollution in Sweden are relatively low. Despite this, it has been shown that reduced birth weight, reduced lung function and the risk of becoming ill with asthma, dementia and heart attack are related to levels of air pollution that occur in Sweden. These findings have also been confirmed in major studies in Europe and North America and in literature compilations.

It has not been possible to establish a safe level below which air pollutants have no adverse health effects. In fact, the correlation between air pollution levels and their health consequences seems to be steepest at low concentrations, i.e. that for the same increase in the dose (concentration) of particles, the increased health risk is higher at low concentrations than at high concentrations (Figure 2). Weaker relationships at higher concentrations may be due to biological defence mechanisms that are activated or that the most sensitive individuals are already affected by lower concentrations. The fact that the health benefit of reducing air pollution levels is large even at low concentrations means that reduced concentrations of air pollutants would benefit Sweden's public health greatly. This is why there is broad scientific consensus that WHO's new, stricter air quality guidelines are justified from a health perspective and are an important public health objective, despite being difficult to achieve in much of the world.

Particles have a high health impact

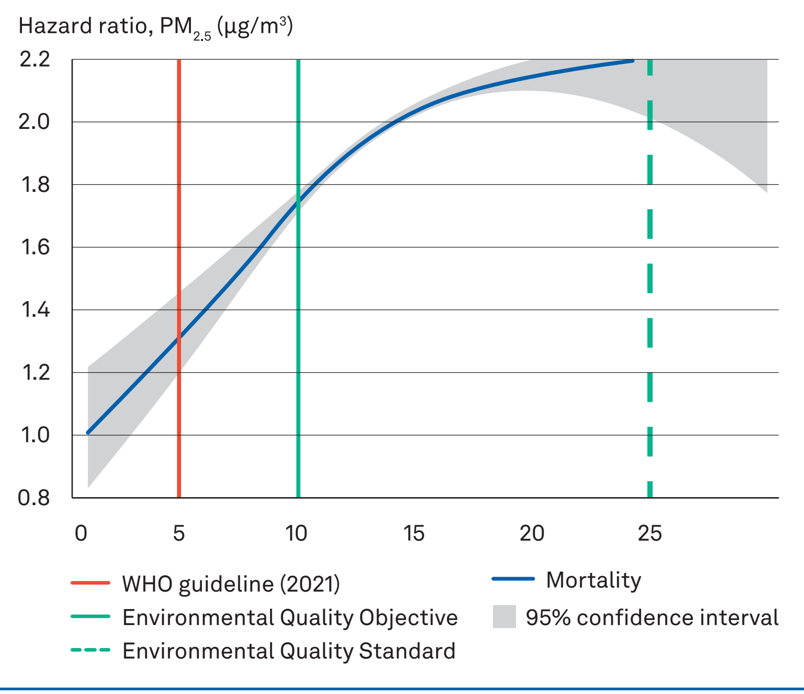
Particles have a high health impact at population level in Sweden and the rest of the world. However, different reports indicate different effects. The differences depend on the application, in epidemiological studies, of observed relationships between concentration and risk, when performing theoretical calculations for entire populations. The choice can be between applying average relationships from as many studies as possible or fewer more relevant relationships. Assumptions can therefore differ between global, national and local analyses, partly because particles from different sources can have different effects. Impact assessments usually refer to long-term effects of annual concentrations but can sometimes refer to more immediate effects of shorter periods with varied concentrations.

The regular Global Burden of Disease study calculates the number of premature deaths and lost healthy years due to various risk factors. For 2019,

Figure 2. Premature death due to air pollution, $PM_{2.5}$

An adjusted variant of the results from Strak et al. 2021 from the European ELAPSE study. This shows a clear correlation between long-term exposure to air pollutants and the risk of premature death even at concentrations below current Swedish environmental quality standards. The steeper slope of the line at low concentrations also shows that the relationship between particles and death is stronger per microgram of particles in areas with low concentrations, such as Sweden.

Source: Strak, M. et al. (2021), doi.org/10.1136/bmj.n1904



ambient air particles were ranked as the seventh largest risk factor of all, with smoking as the only external (non-individual) factor of greater importance. This and several other estimates show that human-origin emissions account for 4–5.5 million premature deaths annually.

Reduced concentrations can have a major effect on health

Following the publication of WHO's new air quality guidelines in autumn 2021, a study was published on the benefits of reducing the annual average concentration of $PM_{2.5}$ to 5 micrograms per cubic metre. This level of reduction in 47 cities, covering a total of one third of Europe's population, was estimated to lead to more than 109,000 fewer premature deaths annually. However European findings suggest that the effect could be twice as high. The benefits of historical reductions are also estimated to be significant in Europe, where PM2.5 levels have been reduced by about a third from 1990 to 2019 with an equally significant reduction in mortality. A study of PM_{10} levels in Stockholm, Gothenburg and Malmö 1990–2015, however, found that measurement data did not show any common or clear trend in Sweden.

High numbers of deaths and significant costs to society

In Sweden, particles are estimated to cause several thousand premature deaths annually. Premature death is calculated as an average loss of ten years of life per case. Long-range transport of air pollutants is judged to be the main cause. Local emissions in greater Stockholm are estimated to have resulted in a few hundred premature deaths per year. The


Photo: iStock

In Sweden, particles are estimated to cause several thousand premature deaths annually.

Epidemiological and experimental studies

Epidemiological studies use the actual incidence of different health outcomes in a population to calculate how the risk of being affected is related to various factors, such as the level of air pollution where you live. When analysing effects, an attempt is made to isolate or, at the same time, consider various risk factors to separate different relationships. The studies can apply for both short periods and decades. Researchers can study who is being affected directly or can base these estimates on diagnosis and cause of death registers.

Experimental studies allow researchers to control how humans or animals are exposed to the risk factor being studied as well as other factors. Studies in humans are limited to short duration and the presence of minor and transient changes, while animal tests may be used for studying more adverse effects, such as the development of cancer.

contribution from particles caused by road wear was significantly greater than that of exhaust particles because their levels were higher.

Air pollutants lead to major socio-economic costs. According to a Swedish method used to calculate health costs caused by road traffic air emissions, premature deaths account for more than half of the health costs, but stroke, diabetes and childhood asthma also entail high costs.

Strongest evidence for fine particles

Although the level of certainty that air pollutants cause ill health is high, it is more difficult to say how dangerous the various components are. As different air pollutants are in reality often emitted together, it is difficult to discern their individual effects without experimentation.

The most certain figures available are for fine particles ($PM_{2.5}$). Some experimental studies suggest that the very smallest (ultrafine particles, less than 100 nanometres) and newly formed particles can have a significant impact on health. In epidemiological studies, however, ultrafine particles have not shown as clear a relationship with health effects as was expected. This may be because there are too few measurement points to capture the large variation in the dispersion of these particles. However, experimental studies support the theory that it is precisely these particles that cause faster growth of atherosclerosis, reduced renal function and increased risk of blood clots after exposure to air pollutants.

Emissions from road wear and forest fires can increase

Although long-range transported and older particles might account for more than half of the particle concentrations in a specific place, local emissions near their source may be more harmful to health. One reason for this may be that the composition of long-range transported air pollutants is less dangerous to health. Today, road traffic and wood burning are the largest local sources of small particles. Particles from wood burning are less well studied but may have similar health effects to the more studied exhaust particles.

There is reason to believe that road wear particles will increase as cars become increasingly heavy, while exhaust emissions will decrease as electric cars become more common. Today, however, we know far too little about how road wear particles can affect health to say how this change will affect human health. Climate change can also make forest fires more common and thus a more significant source of air pollutants in Sweden.

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Further reading

Brunekreef, B. et al. (2021). Mortality and Morbidity Effects of Long-Term Exposure to Low-Level $PM_{2.5}$, BC, NO_2, and O_3: An Analysis of European Cohorts in the ELAPSE Project (healtheffects.org)

What are the WHO Air Quality Guidelines? (who.int)

Quantification of population exposure to NO_2, PM_{10} and $PM_{2.5}$, and estimated health impacts 2019 (ivl.se)

Quantification of population exposure to PM_{10}, $PM_{2.5}$ and NO_2 and estimated health impacts for 2019 and 2030 (smhi.se)

Fact sheet Luftföroreningar och hälsa (amm.se)

Luft och miljö 2017 – Barns hälsa (diva-portal.org)

Toxicology – a way of understanding particles

Particles that become lodged in the lungs can cause major health problems. The harm caused by these particles depends on how deep they enter the lungs and how long they remain in the body. But it also depends on their toxicity. Toxicological studies are needed to find out which particles are the most harmful and to assess the risks of new types of particles.


Photo: Adobe Stock

It is possible to estimate which types of particles are most harmful by cultivating cells that are found in the lung, exposing them to particles and studying the toxic effects. This also makes it possible to study 'new' particles generated from new types of fuels or manufactured for use in new materials.

What happens inside the body when particles are inhaled?

Particles in the air will be deposited in the lungs to varying degrees. The amount deposited depends on many factors, such as the size of the particles and the breathing pattern of the individual. Particles remain in the lung for different periods of time, depending on where in the lung the particles become lodged and the properties of the particles. A large proportion of micrometre-sized particles lodge in the upper respiratory tracts where the cilia help to transport the particles to the mouth, from where they are swallowed. Particles that are small enough to reach the alveoli (where the body takes oxygen from the air) are not removed as effectively from the lungs, and a type of immune cell called macrophages plays an important role in dealing with these particles. Particles that dissolve over time will also be removed from the lungs through this process, while hard-to-dissolve particles may


Photo: Hanna Karlsson

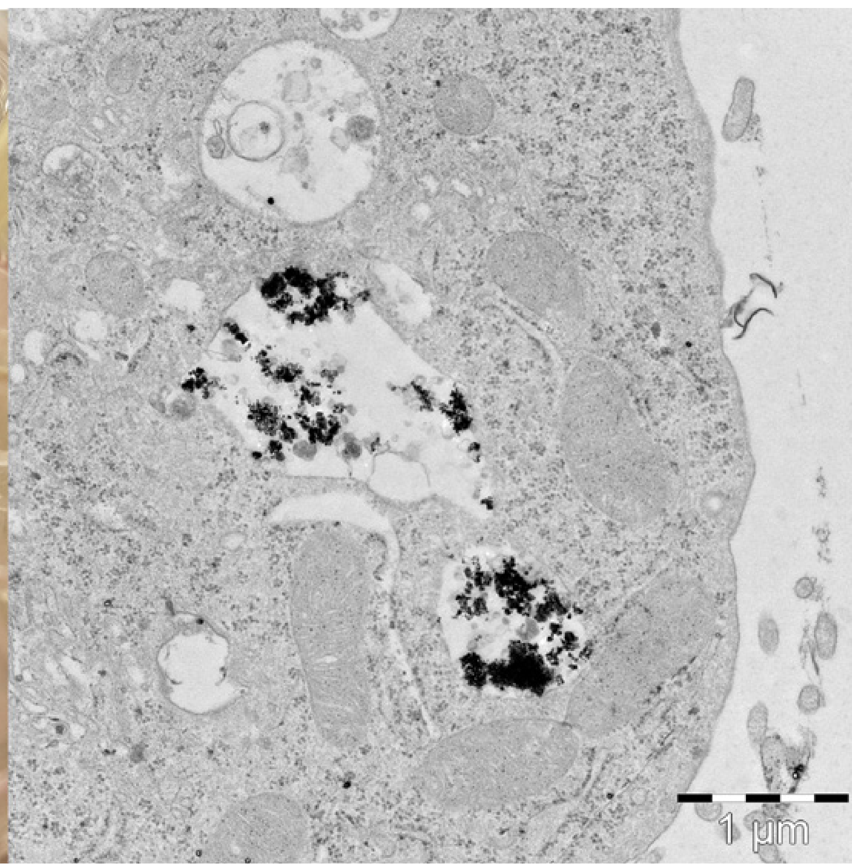

Photo: Electron microscopy unit, Karolinska institutet

In the laboratory, cells can be grown in cell culture plates and then exposed to particles to study the toxic effects. Many cell types take up particles that often end up in small vesicles inside the cell. Electron microscopy can be used to study this effect. The image to the right shows black particles inside a lung cell.

remain longer. Depending on the properties of the particle (such as size), particles can also move from the alveoli to the blood, but it is likely just a small proportion of the total number of particles that do so. There are also animal studies that suggest that particles that deposit in the nose can be passed on to the brain via the olfactory nerve. Various harmful effects can then be triggered, depending on the particles' properties. These effects include inflammation, oxidative stress and genotoxicity (see fact box).

Why are particles harmful and what does their toxicity mean?

Inflammation is a defence mechanism that can be harmful, especially if it is prolonged. Oxygen radicals are formed as part of the body's defence mechanism, and an imbalance called oxidative stress may result if these cannot be removed by antioxidants. The surface of particles may also be reactive, resulting in the formation of oxygen radicals. Particles can also consist of various soluble metals and some of these can efficiently cause oxidative stress.

Genotoxic effects result in damage to cell DNA. This can also be caused by oxygen radicals, resulting in DNA strand breakage. Other substances, such as certain polycyclic aromatic hydrocarbons (PAH), may enter the cell nucleus and bind to DNA to form DNA adducts. Damage to DNA is usually repaired, but if it is not or if it is repaired incorrectly, mutations may occur. These types of permanent changes to genetic material can lead to cancer.

The harmful effects of inhaled particles depend on many different aspects; first and foremost, whether particles enter the lung and how long they remain there. The toxicity in turn can sometimes be due to the shape of the particles. For example, macrophages have significant difficulty in

Foto: Adobe Stock

Oxidative stress, genotoxicity and inflammation

Oxidative stress: A condition that may occur if there is an imbalance between reactive oxygen molecules and the amount of antioxidants.

Genotoxicity: Damage to genetic material (DNA). For example, DNA strand fracture caused by oxygen radicals or DNA adducts formed when a substance binds to DNA. Such effects can cause errors in the genetic code (mutations) as the cell divides.

Inflammation: The body's defence mechanism in which the immune system reacts in different ways. A natural defence mechanism that can be harmful, especially if the inflammation is prolonged.

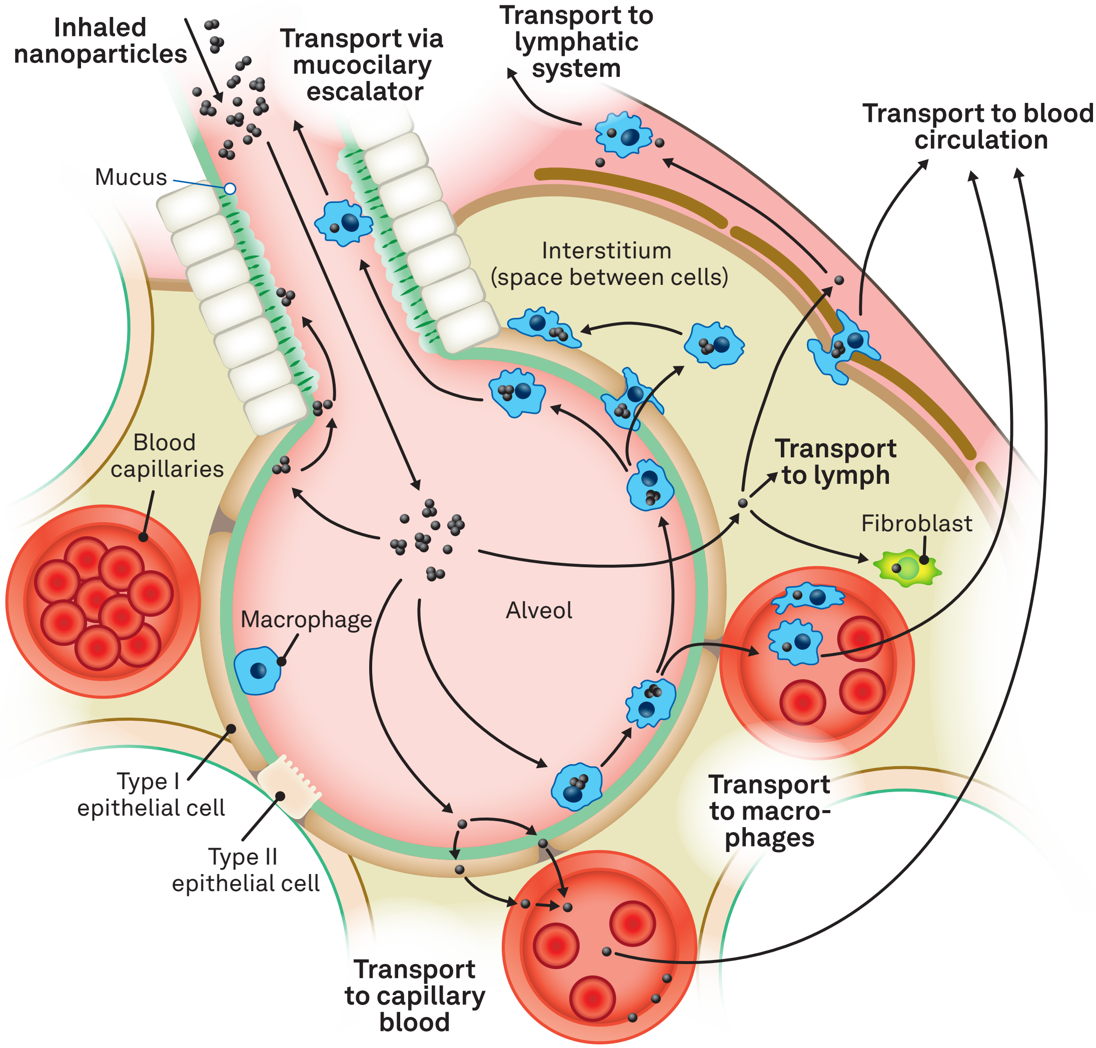

Figure 1. The path of particles through alveoli

Schematic representation of particles in the alveoli. Macrophages can transport particles to airways with cilia (for mucociliary transport) or to the lymphatic system. Some of the particles, or soluble substances from the particles, can also be transported to the blood. It is possible to see which types of particles are most harmful by cultivating cells found in the lung (epithelial cells, macrophages, etc.), exposing them to particles and studying the toxic effects. This also makes it possible to study entirely new particles.

Source: Redrawn after Stone, V. et al. (2017), Nanomaterials versus Ambient Ultrafine Particles: An Opportunity to Exchange Toxicology Knowledge.

Illustration: Petra Wikström

managing long and stiff fibres (such as asbestos), and when they fail to pick up the fibres, oxygen radicals are formed that can damage the lung (known as frustrated phagocytosis). The toxicity also depends on whether the surface of the particle is reactive and what the particle consists of. Some metals and PAHs are particularly harmful. One interesting question is whether small particles, such as ultrafine or nanoparticles, are more harmful than larger particles. There are a few different reasons why they could be. Firstly, a larger proportion of small particles will deposit in the alveoli and will not be removed as quickly from the lung, leading to a greater risk of spreading further into the blood. Small particles also have a very large surface area per unit of mass, and different reactions can occur on the surface leading to oxygen radicals. The large surface area can also cause greater release of the metals that the particle is made up of, which can lead to higher toxicity.

How can toxicology be used to study the effects of particles?

We are all exposed to a large mixture of particles of different sizes and different compositions. This makes it difficult for epidemiological studies to find out which particles are the most harmful and why. For example, it is difficult to study the effects of different sizes if the source of large and small particles is the same, which means that people are always exposed to both at the same time (e.g. road traffic particles).

Photo: Adobe Stock

New types of particles could originate from new types of fuels or tyres. Toxicological studies are important to allow the prediction of the effects of these new exposures.

Toxicological studies allow researchers to refine their experiments. Knowing that particles that cause inflammation, oxidative stress and genotoxicity are harmful, it is possible to simply cultivate cells from the lung and test them to see to what extent such effects are triggered. Several other mechanisms can also be studied to understand more about the types of effects that particles can cause. For example, epithelial cells from the inside of the walls of the airway or from the alveoli can be cultured, as can immune cells that can be recruited into the lung when particles deposit.

A common approach is collecting particles of different sizes on filters, then releasing them from the filters and mixing them into the fluid in which the cells are cultivated. It is also possible to deploy more advanced exposure techniques when the particles are directed as an aerosol to cells grown in the air-liquid interface, thus trying to mimic a real-life situation. After the cells have been exposed to particles, a variety of methods can be used to study their toxic effects. In addition to studying cultivated cells, studies are also conducted on animals, such as rats and mice.

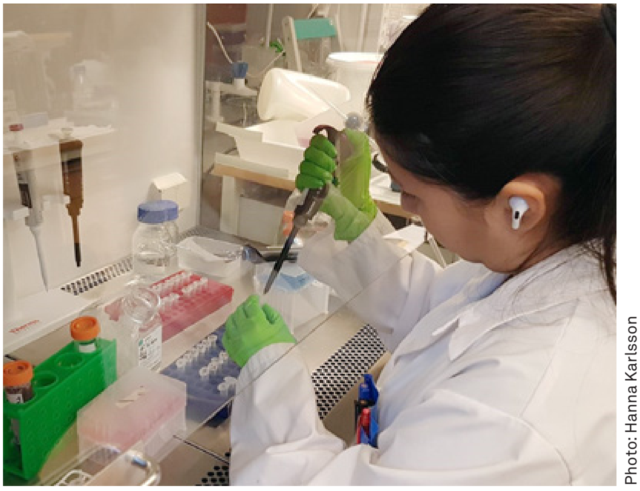

Photo: Hanna Karlsson

Researchers can gain an understanding of what types of particles are most harmful through toxicological studies where cells from the lungs are cultivated.

Toxicology for risk assessments of "new" particle types

It is very important to be able to conduct toxicological studies on animals and cells to predict the effects of new exposures (as opposed to epidemiology which can only be used when health effects have already occurred). Examples of "new" exposures could be various manufactured nanoparticles or particles formed from new types of fuels or tyres. Today, more emphasis is placed on animal testing than on cell studies in the risk assessment of particles. In these studies, animals are exposed to particles, such as through inhalation, and an attempt is made to determine the dose at which different effects are triggered. The dose can then be recalculated for the dose for humans and the necessary exposure to reach the corresponding dose. By also including particles with known effects, it is possible to gain an idea of how harmful the new particles are compared to the more familiar ones. There is great hope that computer models will eventually provide better understanding of health effects, for example to predict doses to lungs and other organs and to use different cell studies more effectively.

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Further reading

Stone, V. et al. (2017). Nanomaterials Versus Ambient Ultrafine Particles: An Opportunity to Exchange Toxicology Knowledge (nih.gov)

National Platform for Nanosafety (ki.se)

Traffic - an environmental problem that just keeps rolling on

Wear and tear of roads, tyres and brakes account for 44 per cent of Sweden's total annual emissions of inhalable particles (PM_{10}). Tyre wear is also considered the largest source of microplastics. Will ongoing electrification solve this or is it just creating other problems?

In Sweden, we have environmental quality standards that aim to protect health and our environment. When an environmental quality standard is exceeded, Chapter 5, section 7 of the Swedish Environmental Code specifies that an air quality plan needs to be drawn up. We also have 16 environmental quality objectives that guide society's environmental efforts towards a more sustainable future. We are currently having trouble meeting the environmental quality objectives, and the latest evaluation showed that we only meet 1 out of 16 objectives. The objectives cover a range of areas including clean air, a non-toxic environment and reduced climate impact. Road traffic is an important reason why these objectives have not been achieved.

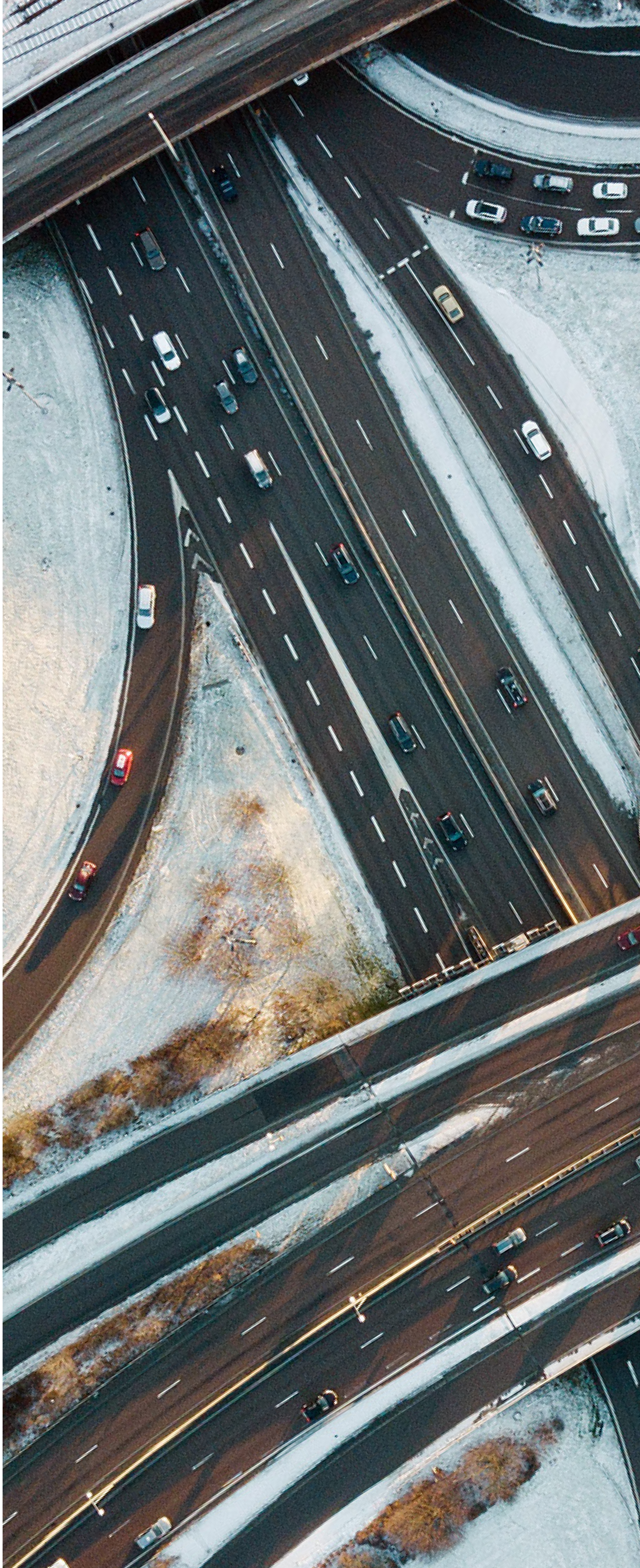
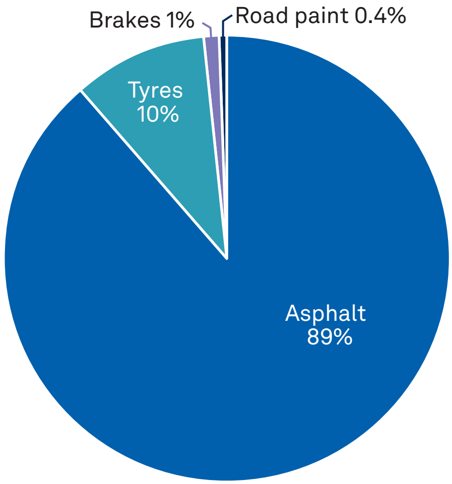


Photo: Adobe Stock

Figure 1. Estimated annual wear and tear in traffic

Sweden's approximate annual emissions of wear particles divided into particles from asphalt, tyres, brakes and road paint.



- Asphalt, 100,000 tonnes
- Brakes, 600 tonnes
- Tyres, 11,000 tonnes
- Road paint, 500 tonnes

Source: Järlskog, I. 2022. Occurrence of Traffic-Derived Microplastics in Different Matrices in the Road Environment.

When driving on an asphalt road, both the road and the tyres wear and produce wear particles. The greatest wear occurs on bare ground during the winter, when studded tyres are used. Since the 1970s, when studded tyres were introduced, asphalt, tyres and studs have evolved to reduce wear. Despite this, approximately 100,000 tonnes of asphalt are worn away in Sweden every year. In addition to costing large sums to replace the asphalt, the wear and tear also give rise to PM_{10} (inhalable particles, less than 10 micrometres), which negatively impact our health.

What happens to the particles?

After wear particles are formed, they either end up on the road surface or are resuspended in the air, diminishing our air quality. When it rains, some of the particles are washed away from the road and into stormwater drains and ditches. From here, they can either lodge in layers of soil or sediment or continue moving towards waterways, lakes and seas. If the road is damp or frozen (which it often is during the winter), the particles stick to the road surface. Once the road then dries up during dry

Figure 2. Dispersion pathways for wear particles

Simplified illustration of the dispersion pathways of wear particles. After the particles have formed, they can either be resuspended in the air, stay on the road surface, end up in the immediate surroundings or be transported further to waterways.

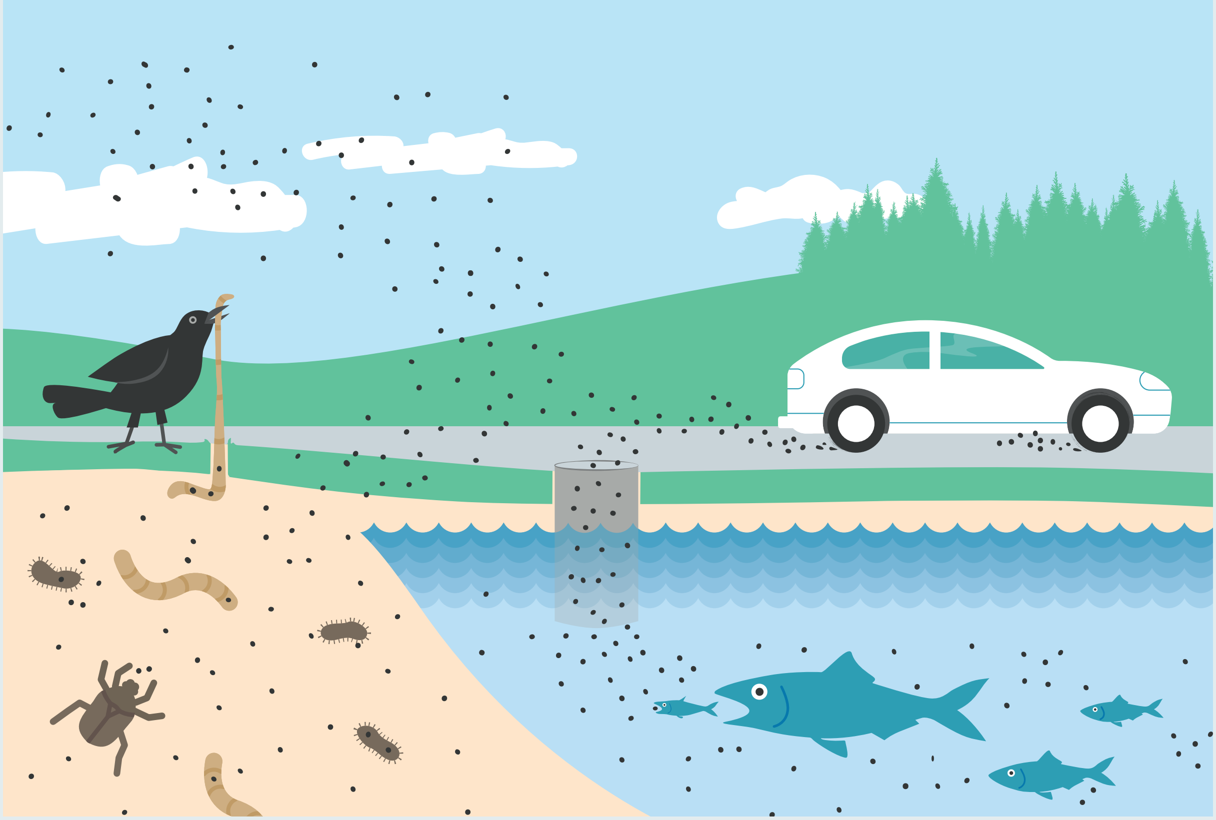


Illustration: Petra Wikström

and sunny spring days, turbulence from traffic can lead to the particles being blown up into the air. This is why we often have high particle concentrations along streets and roads in the spring.

To prevent the particles from being blown up into the air, street cleaning is used to sweep away the dust and dust binding can be used to keep the road moist longer. The texture of the road, i.e. how raw the surface is, can affect how much road dust gets stuck in the asphalt and how effective the cleaning will be. More road dust generally sticks to asphalt with a rough texture than to asphalt with a smoother texture, making it more difficult for the dust to both be resuspended in the air and be cleaned off.

Tyre wear the largest source of microplastics

When we drive a car, the tyres wear down and form small particles that mainly consist of rubber (natural and synthetic) and fillers like extender oils and reinforcement materials. Tyre wear is recognised globally as the single largest source of microplastics. In the EU, tyre wear is estimated at around 500,000 tonnes per year, and in Sweden around 11,000 tonnes per year, which is roughly the same as the weight of 1.1 million passenger car tyres. Once the tyre particles form on the road surface, they mix with particles from asphalt and brakes along with particles from other sources that have ended up on the road surface. Tyre particles take a long time to decompose, which means that they can have a negative impact on nature well into the future as they lie in the soil, in the water or in sediments.

Did you know?

- Banning studded tyre on specific streets decreases studded tyre use, thus decreasing particle emissions in general.
- Winter tyres generally wear faster than summer tyres due to their softer rubber compound.
- In 2021, approximately 1 per cent of Sweden's passenger cars were pure electric cars (3 per cent including plug-in hybrid electrical vehicles and electric hybrids). Eighteen per cent of all new cars sold were pure electric cars, 45 per cent if all rechargeable vehicles are included.
- An electric car is on average about 20 per cent heavier than a corresponding fossil-fuel car.
- Vehicle traffic makes up 47 per cent of Sweden's emissions of PM_{10}. Of these, only 6 per cent are related to exhaust gases. The rest are wear particles.

Brakes emit finer particles

Tyres and, even more so, brakes wear more per kilometre in urban areas, where junctions, roundabouts and heavy traffic cause more acceleration, braking and cornering. Applying the car's brakes forms particles that are generally smaller than other wear particles and that contain a relatively high amount of metals from brake discs and brake pads.

The vehicle fleet is changing

Emissions of wear particles from road traffic are currently entirely unregulated, while emissions of particles from car exhaust are regulated through increasingly strict emission standards in the Euro classes, the EU's classification of vehicles based on exhaust emissions. The size of the emissions of wear particles is mainly affected by traffic volume, that is, how far we collectively drive our cars each year and the shift of the vehicle fleet towards heavier, electrified vehicles (see Figure 3). As traffic steadily increases, it becomes more difficult to reduce emissions of wear particles. The upcoming Euro 7 regulation proposes limit values for both brake and tyre particles, and work is underway internationally to create feasible test methods for use in future regulation or labelling.

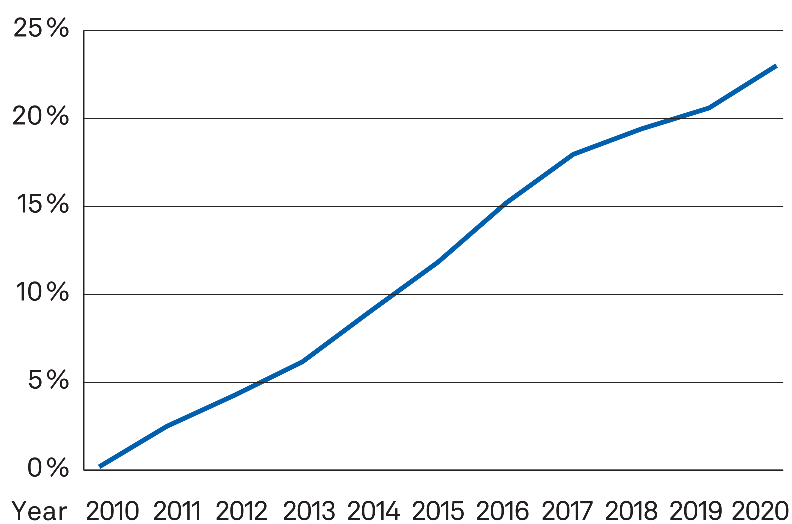
How electrification impacts particle emissions

Growing numbers of electric cars has decreased local emissions of carbon dioxide and health-threatening nitrogen oxides and exhaust particles. However, vehicle weight has increased, which likely increases wear particle emissions since a heavier car wears more on tyres and roads than a lighter car. The high torque of electric cars can also cause a higher wear on the tyres. On the other hand, electric motors can be controlled more precisely, which can be used to limit the torque for smoother acceleration, such as when starting. Electric cars use engine braking to charge their batteries, which reduces the use of mechanical brakes and reduces emissions of brake particles.

Since emissions of wear particles are not decreasing, it is important to better understand

Photo: Adobe Stock

Figure 3. Percentage weight increase in the total Swedish passenger car fleet between 2010–2020.



Source: Transport analysis (2022).

You can make a difference

- Reduce your driving or choose other modes of transport like public transport, cycling and walking.
- Drive smoother using EcoDriving and slow down. Make sure the tyres have the correct pressure and the wheel alignment is correct.
- Use non-studded winter tyres.
- Do not use winter tyres in the summer, whether studded or non-studded. Studded tyres wear the asphalt and non-studded winter tyres wear faster and are not as safe on summer roads.

Photo: Titus Kyrklund

their health effects. Inhalable particles are however generally associated with adverse health effects and emissions should therefore be limited. Certain chemicals with hazardous properties were phased out of tyres in 2010, and copper in brake pads is being phased out by 2025. Many researchers are working on understanding the importance of tyre wear for microplastic emissions and their possible environmental effects.

What can you do to reduce emissions?

Electrification is positive for emissions but does not solve problems with wear particles. Emissions of these particles need to be reduced for both health and environmental reasons. You can do a lot by adjusting the way you drive your car and how you take care of it. Tyre wear can be reduced by driving smoothly with slow acceleration and braking and with correct tyre pressure and wheel alignment. Brakes also wear less when driving in this manner and through increased engine braking. Road surfaces are worn a hundred times more by studded tyres than by non-studded winter tyres. Still, public transportation, and even more, cycling and walking, are the most effective ways to contribute to reduced emissions.

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Further reading

Information on winter tyres (vti.se)

Mikroplast från däck- och vägslitage: en kunskaps-sammanställning. VTI Report 1028 (diva-portal.org)

Fussel, J. et al. (2022). A Review of Road Traffic-Derived Non-Exhaust Particles: Emissions, Physicochemical Characteristics, Health Risks, and Mitigation Measures | Environmental Science & Technology (acs.org)

Sommer, F. et al. (2018). Tire Abrasion as a Major Source of Microplastics in the Environment - Aerosol and Air Quality Research (aaqr.org)

Baensch-Baltruschat, B. et al. (2020). Tyre and road wear particles (TRWP) - A review of generation, properties, emissions, human health risk, ecotoxicity, and fate in the environment (sciencedirect.com)

Järlskog, I. (2022) Occurrence of Traffic-Derived Microplastics in Different Matrices in the Road Environment (diva-portal.org)

Residential wood burning – cosy for some but not for everyone

Burning wood has long been important in Swedish households for heating, cooking and comfort. Today, wood is mainly burnt in individual households in residential boilers, stoves and other types of fireplaces. Domestic wood burning is a major source of particulate emissions, but there are ways of limiting emissions.

For several years we have seen the number of wood-burning stoves increase in urban areas. Increased use of renewable energy is positive, both from a climate perspective and for energy security, but the residential combustion of biomass fuels in homes is also a major source of emissions of pollutants that are hazardous to the environment and health. Burning wood can also cause unpleasant odours in the immediate surroundings and be a cause of nuisance. The level of emissions of various pollutants varies greatly depending on the type of combustion technology and fuel used and how the wood is burnt. Emissions can be reduced when you use good equipment, the correct fuel – and burn wood in a way that ensures efficient combustion.

The impact of burning wood on health and the environment

Emissions from household wood burning are a significant source of exposure to combustion particles in Sweden. Air pollutants cause various types of adverse health effects, including respiratory diseases, cardiovascular problems, lung cancer and other respiratory disorders. Health problems are often greatest in densely populated areas where many buildings burn wood logs or pellets, but even a single building burning wood can sometimes cause major problems for neighbours. Residential wood burning is also a major source of emissions of benzo(a)pyrene (BaP) and other polycyclic aromatic hydrocarbons (PAH), and we still have work ahead of us in order to achieve the environmental quality objective for BaP, in particular. In Sweden, a few hundred premature deaths annually are associated with emissions of particles into the ambient air from residential wood burning. On the European scale, the corresponding figure is estimated at around 40,000 deaths annually. At the same time, there are many indications that salt particles, which can dominate in the efficient combustion of biofuels, have a lower health impact per mass unit than soot, organic and PAH-rich particles which often dominate in traditional wood burning.

Particulate emissions also affect the Earth's climate and are one of the greatest uncertainties when we estimate our future climate impact. What we know today is that soot (i.e. small black particles formed by poor combustion) is a short-lived climate pollutant that absorbs incoming solar radiation and thus has a heating effect on the climate.

Emissions are affected by the type of burning appliance...

There are currently around 2 million heating stoves and tiled stoves (fireplaces) in Sweden and about 221,000 boilers fired with wood or pellets. Some are only used a few times a year, while many wood boilers are used every day to provide domestic heating and hot water. Modern boilers and stoves are generally more efficient, more robust and have lower emissions of particles, PAH and volatile organic compounds (VOC). However, all small wood burners are relatively sensitive to fuel quality and operation, especially wood burning stoves. The largest share of residential emissions of $PM_{2.5}$ and benzo(a)pyrene comes from conventional wood-burning boilers, but there are large differences between older boilers (without water accumulator tanks) and modern systems. Fireplaces contribute more to the emission of soot, and even here, older technologies usually cause higher emissions, as the space for combustion and air supply of newer stoves have been improved.

In Sweden, eco-labelled heating equipment has been available for many years, which has helped reduce emissions as older equipment has been replaced. In the EU, stricter legal requirements governing emissions from new solid fuel systems has recently been introduced. These so-called Eco-Design requirements set minimum limits for the energy efficiency of installations and maximum limits for the emission of several air pollutants, including particulate matter and gaseous hydrocarbons. Requirements vary depending on the type of installation. In 2020, requirements were introduced for solid fuel boilers (e.g. wood and pellet boilers) and in 2022 for fireplaces (e.g. heating stoves and tiled stoves).

...by fuel type...

When burning wood pellets, combustion can take place under much more controlled and stable conditions. The user has better control of the quality and supply of the fuel and can control the air supply. This allows combustion using a controlled flame with a high temperature and good oxygen supply, greatly reducing emissions of $PM_{2.5}$, soot, PAH and gaseous hydrocarbons. However, some particulate emissions remain when measuring emissions from modern pellet boilers and stoves, although often at relatively low concentrations. These particles are dominated by salts formed during combustion, for example potassium chloride and potassium sulphate. However, combustion is not always completely optimal, even with pellet burning, and can be affected by varying operational conditions, low loads (e.g. during low heat demand) and poor quality of the pellet fuel.

Photo: Adobe Stock

...and by operation

Emissions are also determined by how the wood is burned. The most efficient combustion occurs when the fuel is sufficiently dry and there is good air supply, a high temperature and sufficient time for all unburned substances to combust in the flame. Smouldering combustion in boilers and stoves leads to sharp increases in particulate emissions. This often occurs when firing at low intensity with a restricted air supply (sometimes completely without flame burning) or when the wood is too moist (more than 20 per cent moisture content). Smoke from this type of burning often has a yellow-brown tinge and a strong characteristic smoke smell with particles dominated by a complex mixture of organic matter. In both cases, the emission of particles may be several times higher than during more efficient, flaming combustion.

Wood that is ignited quickly and burned at high temperature with a good oxygen supply often minimises $PM_{2.5}$ emissions. While the burning of all solid fuel creates soot, the bulk of the resulting soot can be oxidized (burned off) when the soot meets the air around the flame at high temperatures. However, in residential heating, mainly in conventional wood burning, combustion is not as efficient and the flames are cooled before the soot is oxidized and discharged with the flue gases. If the smoke coming out through the chimney is very black, this is a sign of high soot emissions.

Combustion can also occur too quickly, for example when burning large quantities of wood that is too dry. This can produce large amounts of combustible gases that cannot be combusted in the flame before the flue gases are cooled in the heat exchanger and the chimney. Although dry wood is generally good, the combustion rate must be adjusted according to the amount of air supplied. This is a common problem in stoves and some boilers, and it can lead to very high levels of PAH and soot emissions for short periods.

Emissions from residential wood burning are difficult to calculate

As emissions from residential wood burning are heavily dependent on many different factors, it is difficult to calculate their amounts. Calculating Sweden's total emissions from residential wood burning requires knowing how much of what type of fuel is being burned, what type of installations are being used and how they are being operated.

In addition, there may be a large difference in emissions depending on how measurements are taken. Some of the organic gases in the smoke condense when the smoke is diluted and cooled. It is still unclear whether these condensable particles should be considered when emissions are reported and different countries take different approaches. Some countries base emission calculations on measurements where particles are collected while the smoke is warm, while others allow the smoke to cool down. This has led to great uncertainty when creating models for the dispersion of $PM_{2.5}$ in the atmosphere and the contribution of residential wood burning.

Photo: Adobe Stock

Sweden's total emissions will decrease in the future

As particulate emissions from other sectors decrease, wood burning accounts for an increasing proportion of Sweden's total particulate emissions. However, forecasts for future emissions of air pollutants also show a reduction from biofuel combustion in residential buildings to 2030. The most important way of achieving this is by replacing older conventional wood boilers with new modern boilers (wood or pellets) or switching to other types of heating such as district heating and heat pumps. While Sweden's emissions from residential wood burning appear to be decreasing, the number of fireplaces has increased sharply over the past 10–20 years, causing local problems for the environment and health.

What can you do to reduce emissions?

As we have seen with wood-fired appliances, the way in which they are used can help reduce emissions quite a lot. How you burn and handle the fuel plays an important role in what is emitted and the amount of emissions. With new installations, always choose environmentally certified products that meet current emission requirements and consult your local authority and chimney sweeps about the specific requirements for your area. For modern wood boilers, which are significantly better, one of the most important measures is having a properly sized accumulator tank, i.e. a tank that stores the energy generated by the fire in the form of hot water. There are also available technologies that clean flue gases in residential combustion units, such as small adapted electrostatic precipitators and catalytic systems. It is not yet clear whether and how the requirements for such technology will be integrated into future boilers and heating stoves. Once the equipment is in place, it is important to follow the manufacturer's operating recommendations and to use only split and dried wood. Suitably dry wood must have been stored outside under cover for at least one year and for a maximum of a week indoors before use. Following these recommendations will ensure a cosy home while not affecting your neighbours and surroundings.

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Suggested reading

Information on wood burning (naturvardsverket.se)

Elda rätt/Burn correctly - video (naturvardsverket.se)

Tänd i toppen - brochure (naturvardsverket.se)

Tänd i toppen/Ignite from the top – video (naturvardsverket.se)

Kindbom, K. et al. (2017). Emission factors for SLCP emissions from residential wood combustion in the Nordic countries: Improved emission inventories of Short Lived Climate Pollutants (SLCP) (diva-portal.org)

Nielsen, I.E et al. (2017). Time-resolved analysis of particle emissions from residential biomass combustion – Emissions of refractory black carbon, PAHs and organic tracers (sciencedirect.com)

Nyström, R. et al. (2017). Influence of Wood Species and Burning Conditions on Particle Emission Characteristics in a Residential Wood Stove (acs.org)

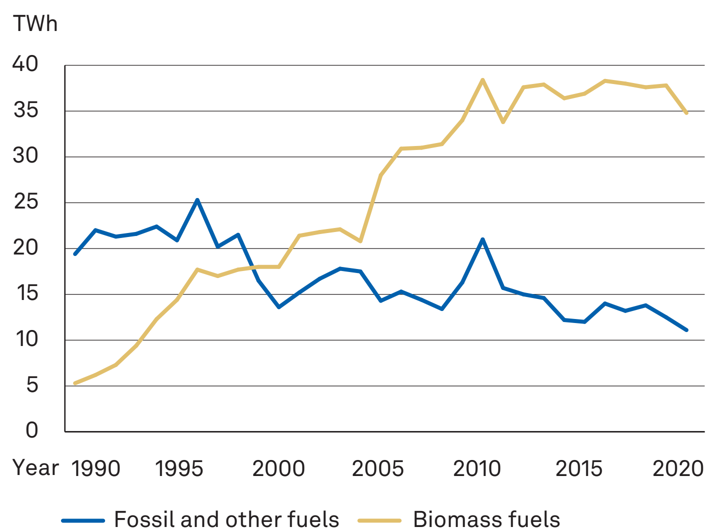
Sigsgaard, T. et al. (2015). Health impacts of anthropogenic biomass burning in the developed world (nih.gov)

More biomass fuels in district heating – problem-free or are there conflicting objectives?

In recent decades, the use of biomass fuels in energy production has increased while fossil fuel use has decreased. Switching from fossil fuels to biomass fuels reduces fossil carbon dioxide emissions and plays a part in reducing the climate impact of heating. However, biomass combustion still causes emissions of air pollutants that can be harmful to the environment and health, especially very small particles.

The share of biomass fuels in district heat production has increased sharply in recent decades and currently accounts for about 75 per cent of total fuel use, compared with about 20 per cent in 1990 (see Figure 1). This has, however, led to a risk of a conflict between Sweden's climate targets and the Clean Air environmental quality objective. Burning biofuels, such as wood pellets, wood chips and wood logs, causes non-fossil carbon dioxide emissions and emissions of air pollutants, such as nitrogen oxides, hydrocarbons, soot and other particles. In general, burning biomass fuels leads to higher concentrations of nitrogen oxides and particles in flue gases than burning oil in district heating boilers.

Figure 1. Fuels in district heat production 1990–2020



Source: Energiläget i siffror 2022, Swedish Energy Agency.

Photo: Adobe Stock

Legislation for heating and combined heat and power plants*

Emissions from combustion plants are regulated in various ways (depending on the size of the installation), e.g. through emission limits in the installation's environmental permit and, for some plants, by limit values via BAT (Best Available Technology) conclusions. The limit values are generally stricter the larger a plant is and depend on other factors such as operating time, plant type and fuel type.

Large heating and combined heat and power plants with a nominal power of 50 MW or more are regulated by the Ordinance (2013:252) on large combustion plants.

Medium-sized heating and combined heat and power plants with a nominal power of 1 to 50 MW are regulated by Ordinance (2018:471) on medium-sized combustion plants. Emissions from the small- and medium-scale district heating sector are primarily regulated by this ordinance. The ordinance has been in force since 2020 for new installations and will apply to existing plants from 2025 or 2030 (depending on their output power).

Solid fuel boilers with an output of up to and including 0.5 MW have been regulated since 2020 by the EU Eco-Design Regulation (2015/1189/EU) for solid fuel boilers, which means that a limited number of small- and medium-scale district heating boilers are subject to this legislation.

*Both heat and electricity are produced by combined heat and power plants, while only heat is produced from heating plants.

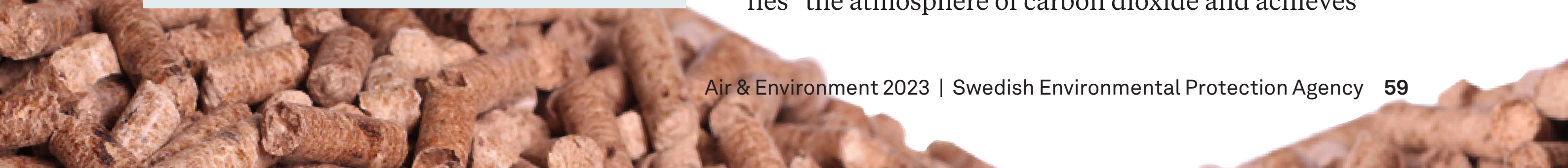
Emission requirements can minimise conflicts between different environmental objectives

The combustion technology, combustion conditions and the type of fuel used determine the level of particle emissions from biomass combustion and the properties of the particles emitted. Using gaseous (biogas) and liquid (bio-oil) fuels generally offers excellent opportunities to optimise burning with low emissions of unburned substances, such as hydrocarbons and soot, which form part of the particles. In the case of solid biofuels, there are benefits with using upgraded fuels (such as pellets and briquettes), which enable efficient low emission systems.

If flue gas cleaning equipment is installed for particle removal, such as electrostatic precipitators or cyclones, some of the particulate emissions are captured before the flue gases are released into the environment. However, the ability to clean flue gases varies greatly for different treatment techniques, because cyclones only separate coarser particles and more advanced technologies (such as electrostatic precipitators and textile filters) are needed to trap the smaller particles. Emission requirements leading to the introduction of efficient combustion technology and flue gas cleaning equipment will enable lower emissions of air pollutants, thereby reducing conflicts between climate objectives and air quality objectives.

Risk of major particulate emissions from small- and medium-scale district heating

Large heating plants that produce heat energy for district heating networks generally have strict requirements for air emissions, such as having highly efficient flue gas cleaning equipment for particles. Large plants also have the potential for introducing bioenergy carbon dioxide capture and storage technologies, known as Bio-CCS, which creates opportunities for a system of renewable heat and electricity production that "purifies" the atmosphere of carbon dioxide and achieves



negative greenhouse gas emissions. How Bio-CCS emissions impact particle emissions, however, is not clear. They could be impacted both positively and negatively depending on what type of CCS technology is used.

Smaller incineration plants that produce heat for a limited number of consumers, small- and medium-scale district heating plants, do not currently have the same stringent emission requirements. The smallest small- and medium-scale district heating plants mainly burn dried upgraded fuels, usually pellets and briquettes, while the larger heating and combined heat and power plants mainly use moist, unrefined fuels such as forest residues. Small- and medium-scale district heating plants do not usually have particle flue gas cleaning equipment, apart from possibly a cyclone. They also lack advanced control systems, making them more susceptible to operational disruptions, and they are usually not manned continuously, which means less monitoring and control. All in all, this means that the biomass-based small- and medium-scale district heating sector is particularly sensitive to operational disturbances and changes in fuel quality, and currently also has difficulty in meeting stricter emission requirements.

Over the past few decades, more and more small- and medium-scale district heating boilers have shifted from fossil fuel oil to solid biofuels, but there is still a great deal of uncertainty and lack of

Small- and medium-scale district heating

Small- and medium-scale district heating plants are small boilers that are not on the district heating network, but provide heating for small communities, parts of cities, large buildings or industries. The plants have a capacity of 100 kW up to 10 or 20 MW and provide consumers with heat via the same principle as district heating. Water is heated in the combustion plant and is then transported to the consumer where the heat is used either directly or indirectly via heat exchangers. The cooled water is then routed back to the small- and medium-scale district heating plant. There are several hundred small- and medium-scale district heating plants in Sweden, and they can be owned by farms, industries, energy companies and other organisations. Most small- and medium-scale district heating boilers are “grate boilers” with only a few “pulverised fuel boilers” and bio-oil burners.

Photo: Bionär närvärme AB

Small- and medium-scale district heating plant with pellet boiler (150 kW) and approximately 20 m² of solar panels in Gävle municipality. The solar panels cover heating needs in summer.

Photo: Bollnäs Energi

Heating plant with two biofuel boilers (1.7 MW and 2.5 MW respectively with flue gas condensation of 0.7 MW) in Arbrå, Bollnäs municipality. The plant also has oil boilers for peak and back-up power.

information about the actual emissions from various types of small- and medium-scale district heating plants and how they contribute to total emissions at a national level.

Alternative sources of biomass fuels place new demands

All in all, it is good for the climate, in the longer term, with a transition from fossil fuels to sustainable biomass fuels in the district and small- and medium-scale district heating sector. However, for particle emissions and air quality aspects, the issue is more complex and small- and medium scale district heating plants pose a particular risk in this context. It is important that these plants use high quality, sustainably produced biomass fuels, have high operational performance levels and have low emissions of air pollutants. Biomass fuels from forests include wood chips, bark, pellets, briquettes and wood logs.

Residues from the forestry industry are mainly used for energy purposes in commercial forestry and the forestry industry. Small- and medium-scale district heating prefers to use homogeneous and high quality biomass, such as with a low ash content, because this allows it to achieve and maintain better combustion conditions. Forestry raw materials are already in demand for the production of a range of products, materials and chemicals, not least with regard to the purely stemwood based biomass, even more so with the transition to a sustainable (bio-based) society. As such, less in-demand, cheaper and potentially more problematic biomass fuels from both forestry and other sectors may need to be used for heat and electricity generation. This will place higher demands on fuel management, combustion technology and purification technology to meet future more strict environmental requirements in terms of air pollutants, in parallel with other sustainability targets.

More energy solutions without combustion in the future

If we are to effectively use the available biomass and enable a biobased circular economy, it is also important to use residues from agriculture and other industries. We will also likely need other, non-combustion-based heat and electricity generation solutions, such as industrial waste heat and a general expansion of other sustainable energy sources. The effects of such system changes on air pollutant emissions need to be carefully studied but would probably lead to a positive impact on air quality in general through reduced particulate emissions into the ambient air.

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Further reading

Compilation of combustion guidelines (naturvardsverket.se)

Combustion plants (naturvardsverket.se)

Industrial emissions IED (naturvardsverket.se)

BAT conclusions for industrial emissions (naturvardsverket.se)

Combustion plants for energy production, including smoke condensation. Industry facts (naturvardsverket.se)

Genomförande av MCP-direktivet. Report 6765 (naturvardsverket.se)

ERA-NET Bioenergy Project FutureBioTec "Future low emission biomass combustion systems" (diva-portal.org)

Particles destroy and pollute

Particles in the air contribute both to increased corrosion and soiling of materials, withsignificant costs as a result. Surface protection can help, but the most effective measure is to reduce particle emissions.

Corrosion breaks down materials, causing them to lose their aesthetic value or mechanical strength. A corroded part of an object increases the risk of unforeseen mechanical failures, resulting either in personal injury or high costs. Corrosion usually refers to impacts on metals, but plastic and stone materials can also break down. Particles can both contribute to increased corrosion and cause soiling of buildings and historical monuments. The soiling is not dangerous in itself, but it contributes to unwanted dirt and increased cleaning costs.

Photo: Adobe Stock

Particles that cause corrosion and soiling

Corrosion is a collective name for many different types of degradation that can affect materials, such as electrochemical corrosion of metals and chemical degradation of stone materials. Various types of salt particles increase corrosion the most, but other particles also contribute. Regardless of chemical composition and structure, almost all particles share one important property, namely the ability to attract moisture – they are more or less hygroscopic. This is a very important property for corrosion, because corrosion normally only occurs in the presence of moisture. More moisture causes more corrosion, and almost all particles contribute to corrosion, regardless of chemical composition.

Soiling is a visual effect where exposed surfaces darken due to air pollutants, primarily measured as PM_{10} (particles smaller than 10 micrometres). The surfaces of different materials give different impressions of dirtiness and have different critical values at which point the dirtiness is unacceptable. Since soiling in practice reduces the ability of objects to reflect light, soot and carbon-containing particles contribute the most to accumulated pollution.

Particles impact our cultural heritage

Much of Sweden's world heritage sites consists of buildings, from the Church Town of Gammelstad in the north to the Naval Port of Karlskrona in the south. Particles do not care whether a building is listed, they cause the same amount of damage regardless. However, we want these buildings to last for future generations, so there may be a need for special protective methods or requirements during restoration. It is important to always involve conservationists when planning and implementing protective measures to ensure adherence to the special requirements for care of materials and longevity.

Photo: Adobe Stock

In church buildings with open doors, even indoor objects can be impacted by particles.

First and foremost, particles cause corrosion and soiling outdoors, such as on buildings. However, depending on the type of building, air exchange and filtration, particles can also find their way into the building and cause damage. An example of this is church buildings with open doors. In these cases, indoor objects can also be affected by particles. The properties of the particles are then the same: they absorb moisture, thus increasing corrosion.

Corrosion affects our infrastructure

Road infrastructure, such as bridges and tunnels, are particularly exposed to particle pollution, both ordinary particles like dirt and salt particles. The combination of dirt and salt is particularly prone to cause corrosion, since together they increase corrosion and bind moisture.

Common salt (sodium chloride) is currently the most common cause of corrosion in Sweden. Salt particles bind moisture, and chloride ions are particularly active in the corrosion process. There are two main sources of salt – salt water near the coast and road salt.

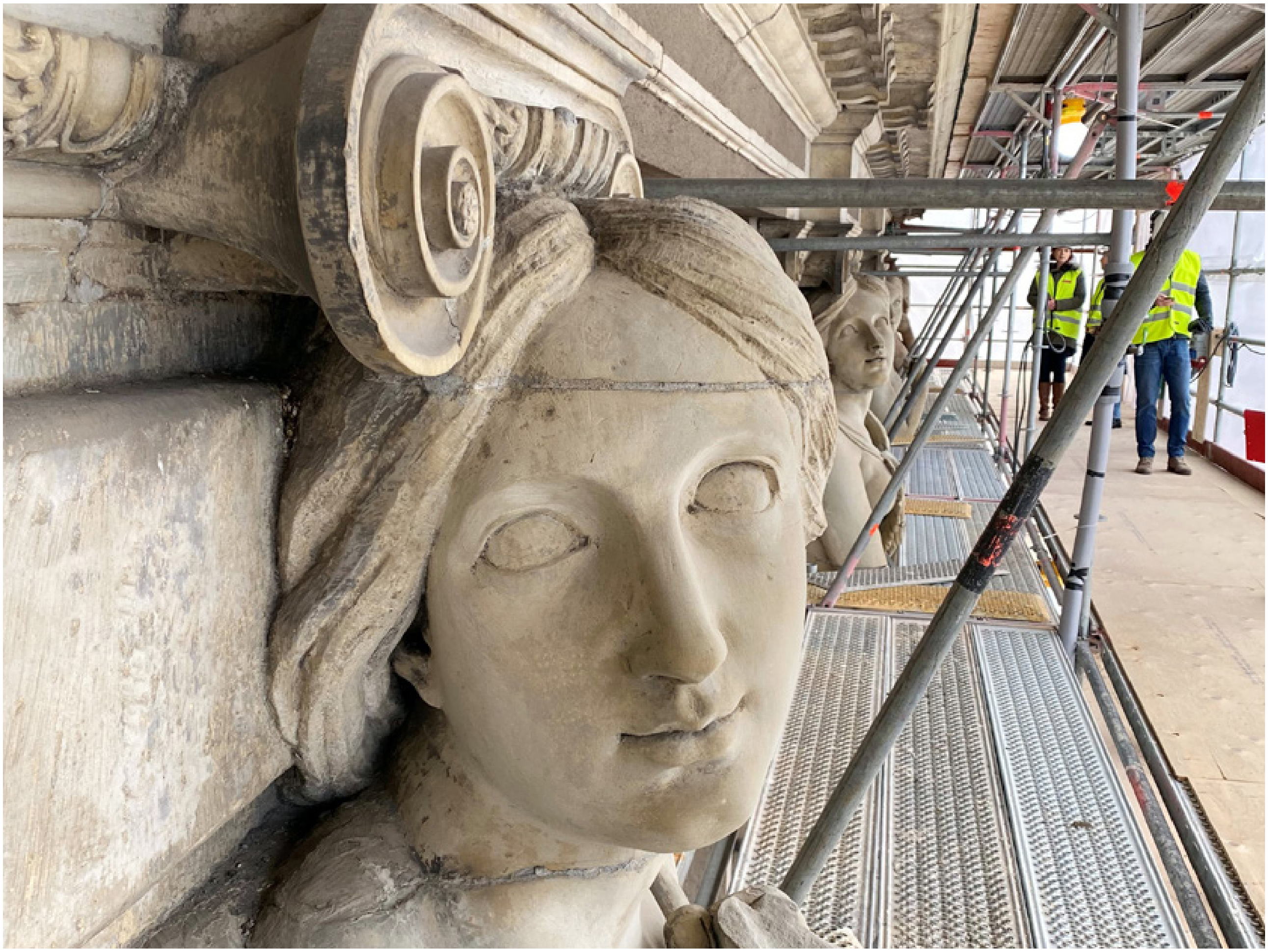


Photo: Mia Fernlund, National Property

The cost of renovating buildings and cultural monuments impacted by soiling is significant, especially in larger cities with many older buildings.

Figure 1. Effect chain model for cost estimates

Effect chain model for estimating costs for the impact of air pollutants applied to soiling on buildings. Emissions are first quantified through an inventory and then particle dispersion into the atmosphere is calculated using climate and air pollution models. The link between exposure and response is made through empirical relationships that quantify the degree of soiling as a function of particle concentrations. Finally, the cost is calculated by combining the cost of renovation (e.g. repainting) and the reduced maintenance interval that is the consequence of soiling. The effect chain model is general and can also be applied to corrosion and to health and natural environment effects.

Salt water near the coast is of greatest importance on the west coast, where water salinity is high. The salt load can vary greatly depending on wind speed and direction. Above all, the closest 10 kilometres along the coastline are most affected by salt, but in extreme storms, salt can be transported long distances inland.

Road salt is only used in the winter months and can also vary greatly from year to year depending on temperature variations throughout the country. Even in the shorter term, it is very difficult to predict the size of the salt load and thus of corrosion, because the use of road salt often occurs with short notice. The reason for this is that salt is more effective and less is needed if spread in the form of a salt solution just before a snowfall.

Soiling costs money

There are well-established methods for calculating costs of the effects of air pollution, whether the impact on health, the natural environment or historic structures. These are usually based on an effect chain (see Figure 1). By connecting the start (emissions) and end (cost) in this chain, it is possible to calculate a cost in SEK/kg emissions that can be used to compare different types of air pollutants and their effects.

Particles cause both corrosion and soiling, but recent cost estimates have focused on the effects of particles in causing soiling because these effects are more clearcut and easier to quantify. Furthermore, trends show that corrosion has decreased significantly, which is not the case with soiling.

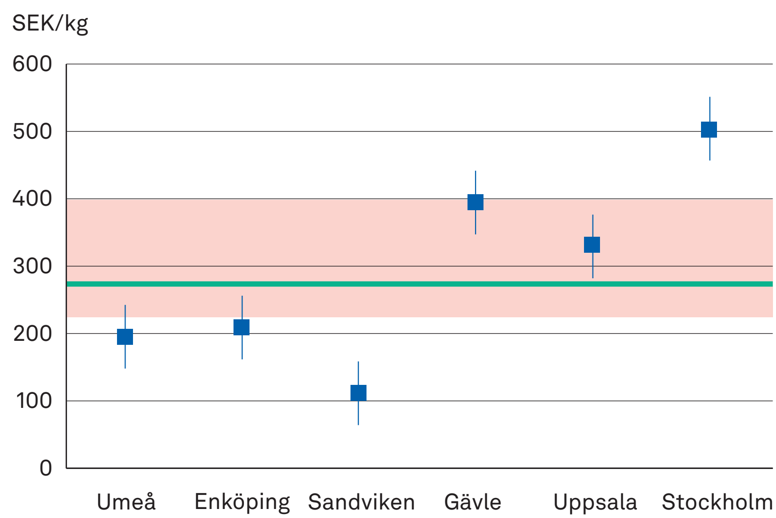
Apart from the geographical differences due to the influence of salt, coast–inland (salt water) and north–south (road salt), particle concentrations are generally higher in big cities than in rural areas (see Figure 2).

Photo: Adobe Stock

Salt water not only affects buildings and objects along the coast, it can also be transported by the wind long distances inland.

Figure 2. Cost of soiling due to particle emissions in SEK/kg PM_{10}

The costs of soiling are generally greater in bigger cities. The green line shows the national mean in terms of soiling costs and the red band shows the uncertainty range.



Source: Swedish Transport Administration.

The cost of soiling can vary from SEK 100/kg of particles in smaller towns to SEK 500/kg in Greater Stockholm. The reason why this cost (per kg) is higher in big cities is that more buildings are affected, meaning that a larger proportion of the particles contribute to soiling. The extreme opposite case is the emissions of particles in an area with no buildings or other objects that can accumulate pollution. In that case, there is no cost for soiling, though the particles can cause other types of damage, such as to the natural environment.

In the same study on which Figure 2 is based, the corresponding national mean value for health effects was calculated at approximately SEK 1,100/kg, while the costs for natural environment impacts were significantly lower than both health effects and costs linked to soiling. The health effects of particles are highest, but the cost of soiling is comparable and not far behind.

Can corrosion and soiling be stopped?

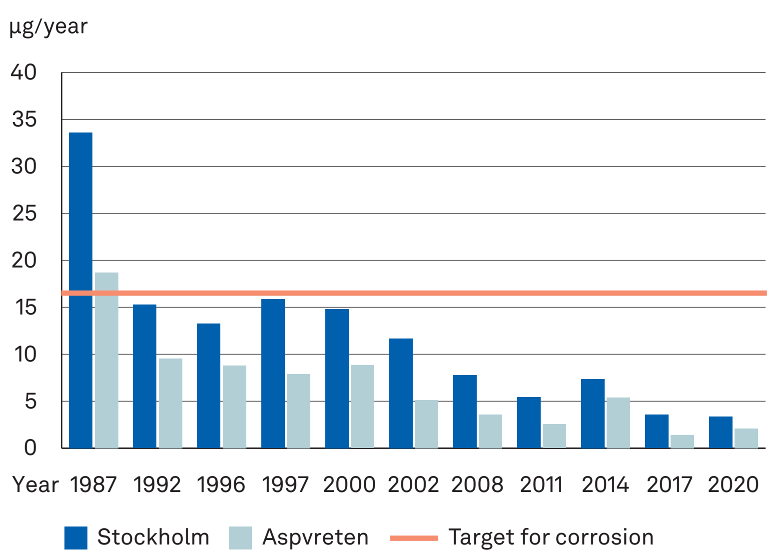
There are different types of corrosion and soiling protection depending on the material and environment, and in-depth knowledge is required to be able to extend the lifespan of materials. For corrosion, surface protection using paint, galvanization and similar methods is common, and treatment that impacts surface properties and the ability of particles to attach to surfaces can reduce soiling. Protecting materials on historical monuments has fewer options and costs more. The best corrosion protection is to reduce particle emissions through preventive measures locally, regionally and globally. This also has positive effects not only by reducing corrosion and soiling, but also on health, the climate and the natural environment.

Where are we headed?

Today, corrosion in Sweden is often considerably less than it was about 50 years ago. Acidification and acidifying air pollutants, mainly sulphur dioxide, have long contributed to increased corrosion in urban areas, but international cooperation has significantly improved the situation (see Figure 3). These pollutants have decreased for many years, though in recent

Figure 3. Trend for corrosion of carbon steel for a city

Trend for carbon steel corrosion for Stockholm and rural areas (Aspvreten, Södermanland). The horizontal line indicates the 2050 international target for carbon steel corrosion.



Source: ICP Materials.

years the decrease has levelled out. Particulate matter concentrations have not decreased to the same extent, meaning urban soiling (see Figure 4) and corrosion from the salt load in coastal and road environments are still major challenges.

To achieve the desired effect, i.e. cleaner air with minimal particle concentrations, it is important to understand that people have different priorities. Some people are more concerned with the effects on health, while others are worried about the loss of cultural and environmental experiences. The Swedish study on soiling costs shows that these are significant and that they amount to approximately one third of the corresponding costs for health. Conducting a similar study in more countries would be useful since older surveys indicate a widespread opinion internationally that costs for corrosion and soiling are negligible.

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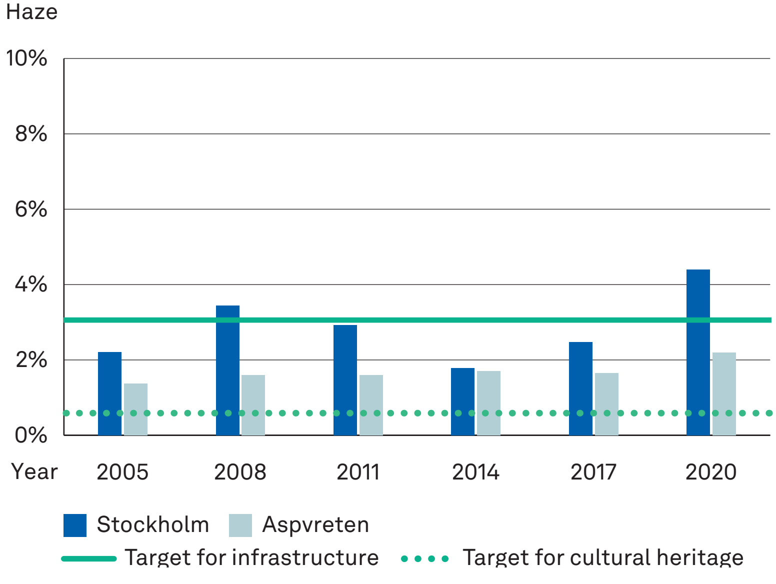
Figure 4. Trend for soiling on glass for a city

Trend for soiling on glass for a city (Stockholm) and the countryside (Aspvreten, Södermanland). The horizontal lines indicate international targets for haze that should be achieved by 2050.



Source: ICP Materials.

Further reading

The International Co-operative Programme on Effects on Materials, including Historic and Cultural Monuments - ICP Materials (ri.se)

Document archive for analyses of transport finances, traffic, capacity and transport prognoses including statistics – Data for revised ASEK value for air pollution (trafikverket.se)

The Convention on Long-range Transboundary Air Pollution (unece.org)

UNECE Working Group on Effects – UNECE Air Convention (unece-wge.org)

The co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe (emep.int)

Long-range transport of particles - dispersion modelling provides insights

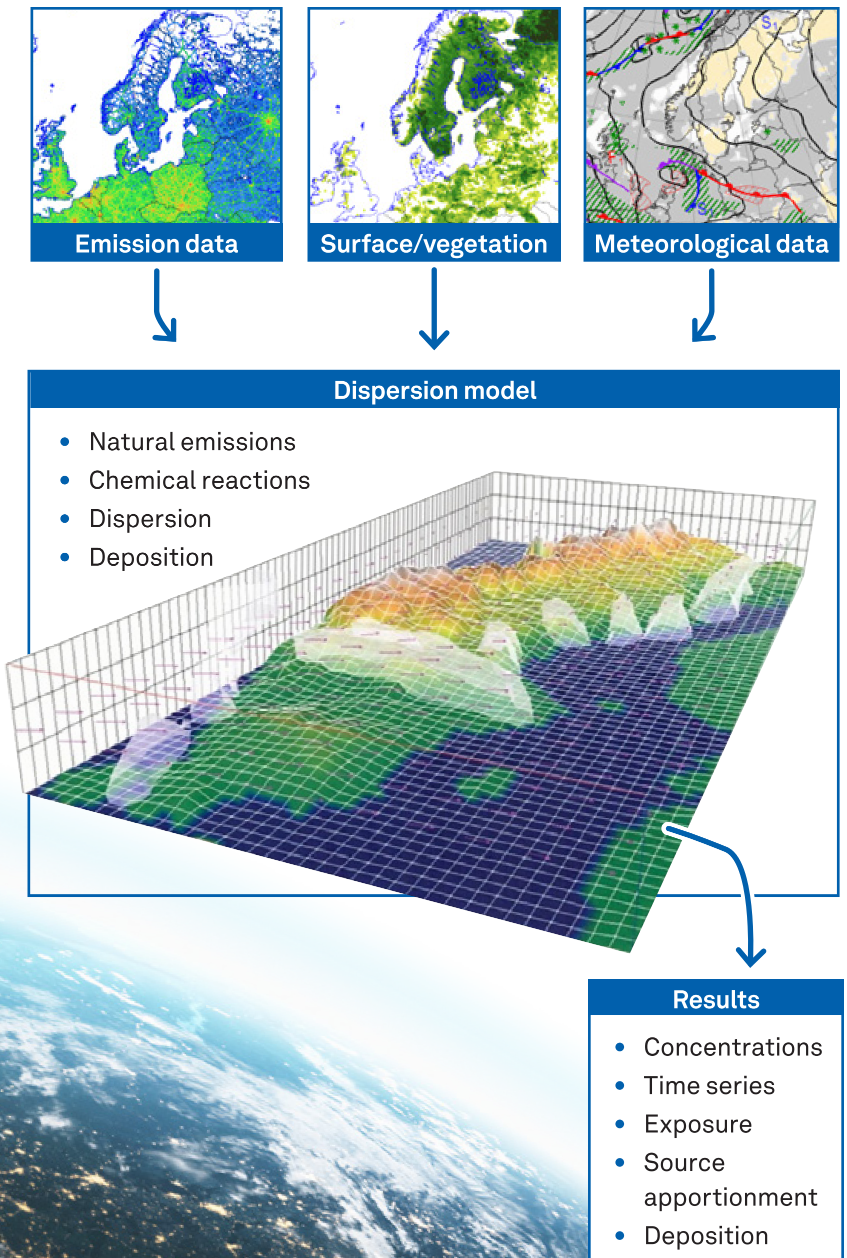
Small particles can remain suspended in the air for a long time and be transported over very long distances. Dispersion modelling allows us to assess where particles come from and what they consist of. This makes it easier to implement the right measures to limit effects on health and climate.

Atmospheric particles come from many sources and can consist of a variety of substances with varying properties. Depending on their chemical content and size, particles have different effects on the climate, ecosystems and health, and these effects can change as particles are transformed in the atmosphere. The length of time that particles remain in the atmosphere depends on their size and weather conditions. Small particles and high-altitude particles can remain suspended in the air for a long time and can be transported very long distances before they disappear from the atmosphere. Forecasting and warning systems use large-scale models to predict long-range transport of particles and other air pollutants, both under normal conditions and in situations with larger emissions.

Photo: Adobe Stock

Figure 1. Dispersion models use huge amounts of data

Dispersion models rely on a large amount of input data to calculate air pollution concentrations and deposition to land and water surfaces. Meteorological data, emission data and land surface information are examples of important input data.



Particle effects on larger scales

Atmospheric particles have many different effects besides those on human health. Other large-scale effects include:

- Particles contribute to climate impacts, both warming – such as light absorption by dark atmospheric particles and on snow/ice surfaces – and cooling through scattering of sunlight.
- Particles have major impacts on cloud formation and cloud properties and can affect precipitation by acting as ice nucleating particles.
- Nitrogen and sulphur-containing particles contribute to eutrophication and acidification.
- Volcanic eruptions can cause several types of particle emissions, often large amounts of sulphur leading to the formation of sulphate particles with potentially large climate impact and acidification; volcanic ash can also be spread far and affect air traffic.
- Particles can have a major impact on visibility conditions - e.g. in desert storms and large-scale spreading of agricultural dust or in connection with large fires.

Large-scale dispersion models

Dispersion models can be used to calculate concentrations of particles and other atmospheric pollutants. The models describe emissions of particles and particle-forming substances, transport with winds, chemical transformation and particle formation in the atmosphere and deposition to water, land surfaces and vegetation (see Figure 1). These models use detailed weather data, often derived from weather forecasting or climate models. Realistic modelling also requires good quality input data from other sources. It is particularly important to have a good description of emissions from different sources. Models can be used to assess where particles come from geographically and from which types of emission sources. Scenario calculations can study the effects of various changes in emissions or climate.

Primary and secondary particle sources

Particles can either be emitted directly to the air (primary particles) or form from gases in the atmosphere (secondary particles). Both primary and secondary particles can come from both natural and anthropogenic sources. Particles often consist of mixtures of different primary and secondary components of different origins (see Figures 2 and 3).

Road traffic and wood burning are important sources of primary particles, but many other emission sources also contribute. Examples of direct emissions include soot and ash particles from combustion processes, mineral particles from industry, construction work, traffic, agricultural land use and deserts, salt particles from the sea and biological particles such as plant fragments and pollen.

Secondary particles may contain both inorganic sulphur, nitrogen compounds and organic matter.

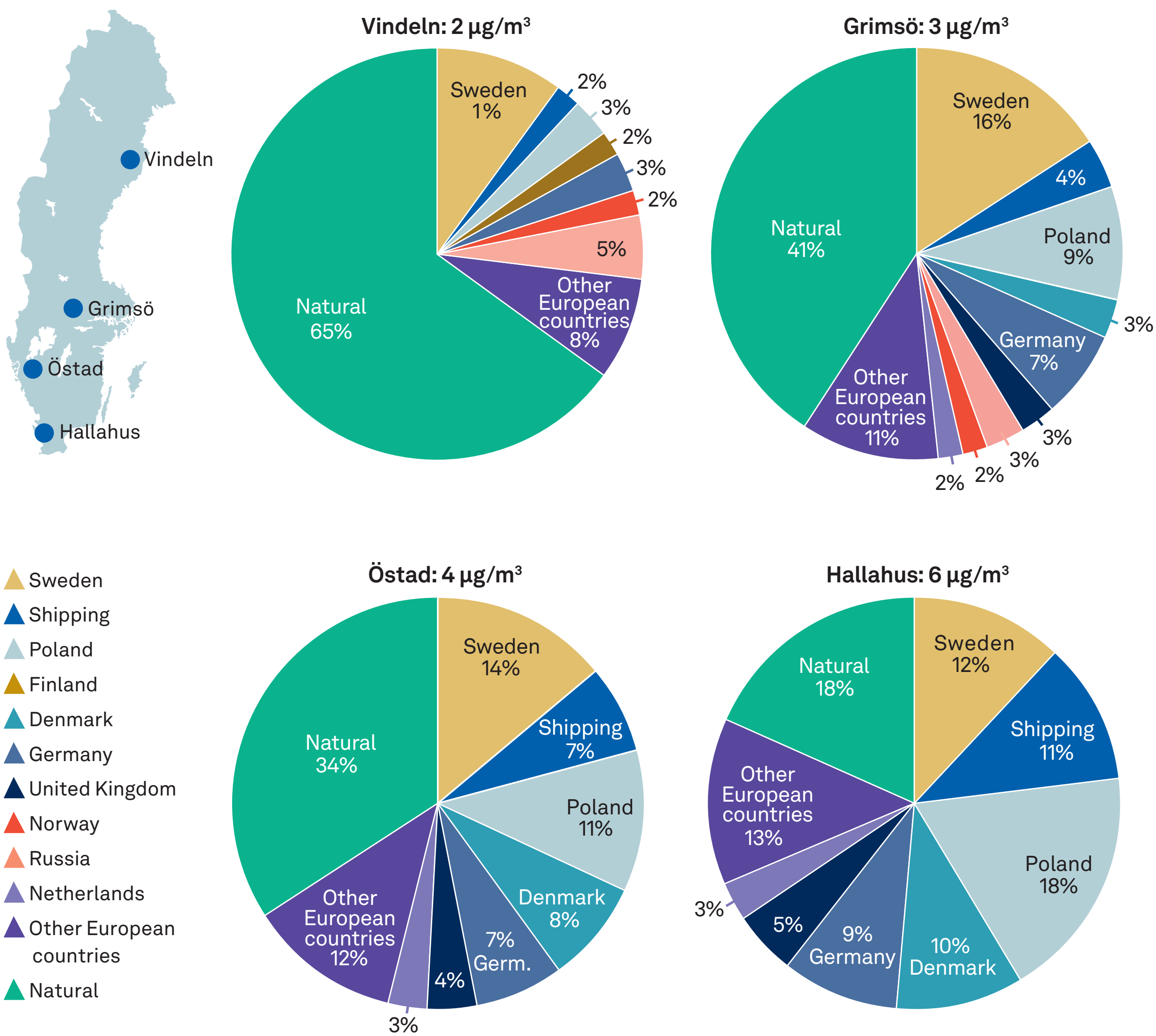
Long-range transport of air pollutants – UN Convention on Long-Range Transboundary Air Pollution

Model calculations of long-range transport of air pollutants in Europe are regularly carried out as part of the UN Convention on Long-Range Transboundary Air Pollution (CLRTAP). Emissions of air pollutants from various sources are reported by most CLRTAP countries and are used in a comprehensive annual work that calculates country-to-country transport of various substances. In this way, it is possible, for example, to get an idea of how particle concentrations in different parts of Sweden are affected by emissions in other countries in Europe (see Figure 2).

Model calculations are also performed for scenarios with changing emissions from different sources in different countries to predict the effects these could have on concentrations and deposition of air pollutants in different parts of Europe. Based on the results of these calculations, combined with cost estimates for various possible measures, integrated assessment models can be used to optimise emission reductions so that air quality targets can be achieved at the lowest possible cost. These types of models are used e.g. in EU work on emission reductions and air quality.

Figure 2. Model-calculated source apportionment for $PM_{2.5}$

Model-calculated sources for regional background levels of $PM_{2.5}$ at four locations in Sweden. Data for 2019 calculated using the EMEP MSC-W model (www.emep.int). Relative calculated contributions from natural sources, Swedish sources, shipping and the individual countries whose emissions are estimated to contribute most to $PM_{2.5}$ at each location are shown (proportion in % of the total estimated annual mean concentration). As the figure shows, the relative share of the natural sources contribution to $PM_{2.5}$ are largest in the northern part of Sweden.



Important sources of inorganic particulate matter include ammonia emissions from agriculture, nitrogen oxides from traffic and combustion, and sulphate compounds from burning of coal and oil and from volcanic activity. Secondary organic aerosol particles (SOA) are formed from volatile organic compounds (VOCs) in the atmosphere.

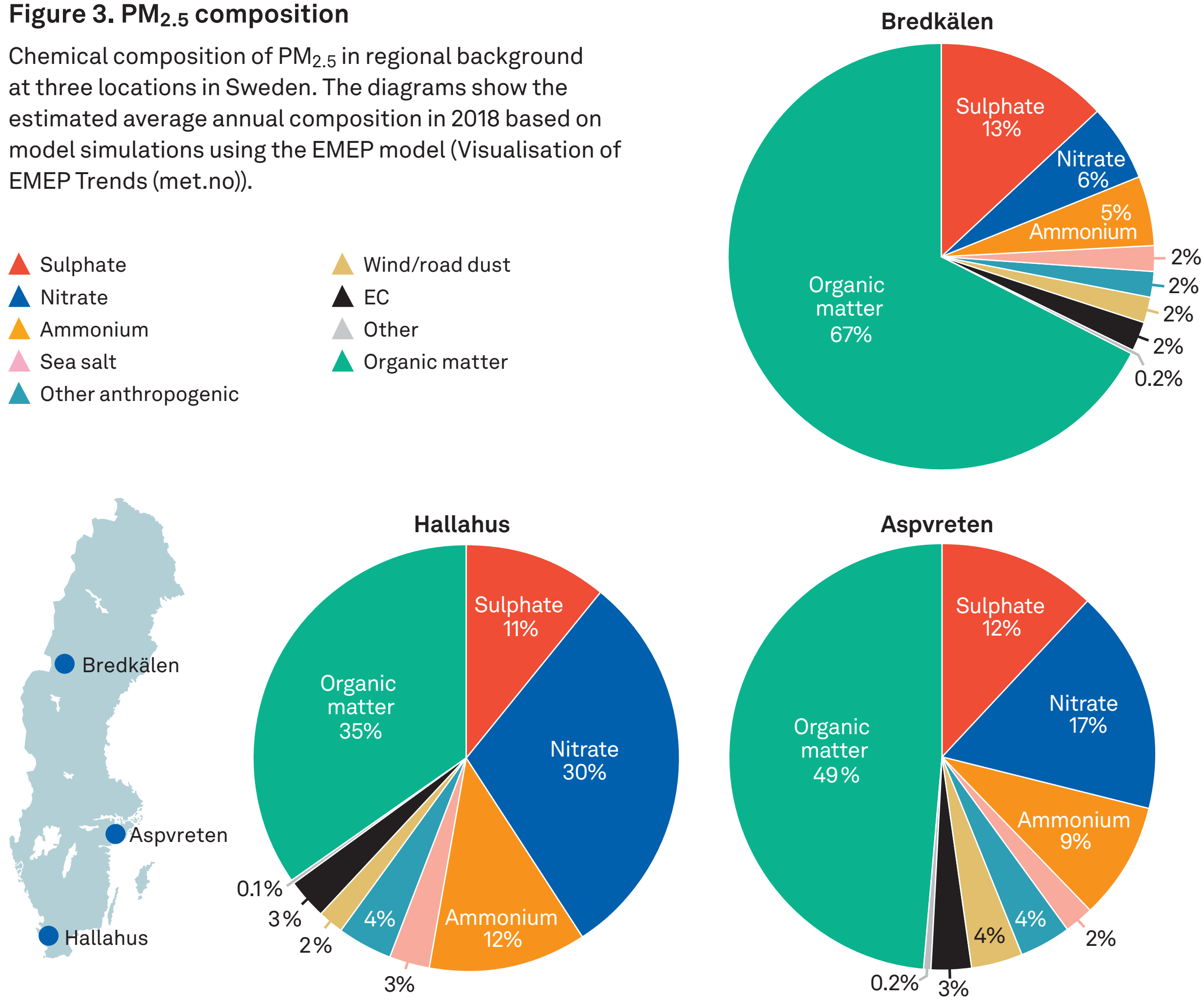
Two important sources of both primary and secondary particles are the residential combustion of solid fuels (wood logs, coal, peat) and wildfires and agricultural fires. Particles from these sources can contribute to very high local levels, but they can also be transported over long distances.

Condensable organic compounds – a challenge for particle modelling

An important source of particulate matter is condensable, or semi-volatile, organic matter, which is often emitted during combustion. These

Figure 3. $PM_{2.5}$ composition

Chemical composition of $PM_{2.5}$ in regional background at three locations in Sweden. The diagrams show the estimated average annual composition in 2018 based on model simulations using the EMEP model (Visualisation of EMEP Trends (met.no)).



Forests are a major source of organic particles, particularly secondary particles formed from volatile organic compounds but also plant fragments, pollen and particles from wild fires.

compounds may be present partly in gas phase and partly as particles; the gas-particle distribution depends on the volatility of the substance and on the temperature. At high temperatures, such as in hot flue gases, they are almost completely in gas phase but cooling causes them to partly condense into the particle phase. Dilution has a counteracting effect so that some of the semi-volatile compounds evaporate again when an emission is diluted in cleaner ambient air.

Organic particle emission measurements therefore depend on the temperature and degree of dilution at which the measurement is performed. One problem is that emission factors for certain sources (e.g. wood burning) were developed under different circumstances in different countries, resulting in large differences in emission data – in some cases semi-volatile compounds are included in the emission factors while they are omitted entirely in others.

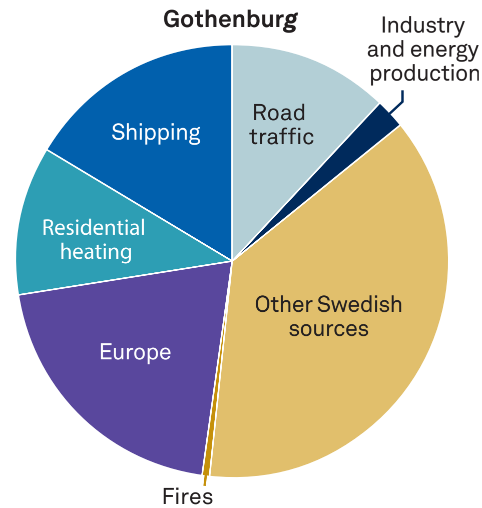
Source apportionment makes it easier to take the right actions

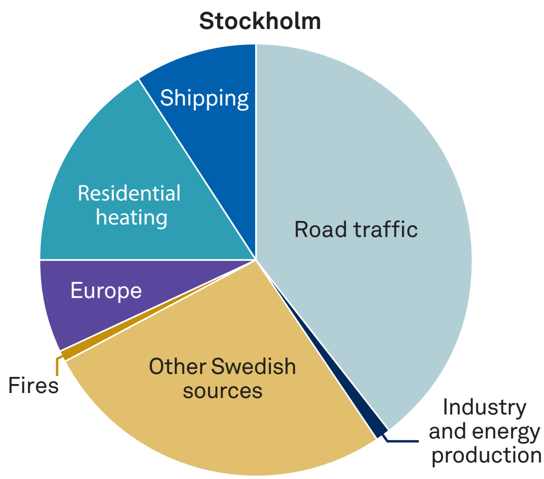
To better understand particle properties and to enable effective measures to influence concentrations, it is important to determine their composition and origin. Particles can be traced from different sources using dispersion models. This requires good information about emissions and a good description of the weather conditions affecting dispersion, atmospheric chemistry and the deposition of various substances to water, land surfaces and vegetation. Source apportionment using models is also useful in health-related exposure calculations. Source apportionment studies can examine total particle concentrations but also individual particulate components of special interest, such as soot (see Figure 4) for climate or health studies.

When environmental quality standards (EQS) are exceeded in ambient air, the origin of the particles must be determined to allow effective measures to be taken. The responsible regional or local authority is required to develop an air quality plan that includes a source apportionment, quantifying contributions from local and urban sources, and dividing the regional contribution into national, transboundary and natural sources. Models can provide information on which sources contribute to particle concentrations at different locations at different times. Higher quality emission data results in more accurate source apportionment.

Figure 4. Soot in urban background

Modelled apportionment between the contribution of various Swedish and foreign sources to annual mean soot concentrations (EC) in urban background in Stockholm, Gothenburg and Malmö in 2019. The levels have been calculated for several areas with a resolution of 2 km × 2 km within each city region – seven different areas have been included for Stockholm and Gothenburg and four for Malmö. The Swedish contributions are divided into residential heating, road traffic, industry, energy production, and 'Other Swedish sources' – mainly emissions from machinery, agriculture and waste management. The contribution from shipping is made up of international and Swedish shipping. 'Europe' shows the contributions from anthropogenic emissions outside Sweden and 'Fires' shows soot from vegetation fires throughout Europe. The modelled contribution of soot transported from other countries is largest in Malmö but is also significant in Gothenburg and Stockholm. The calculations have been carried out using the SMHI MATCH model.





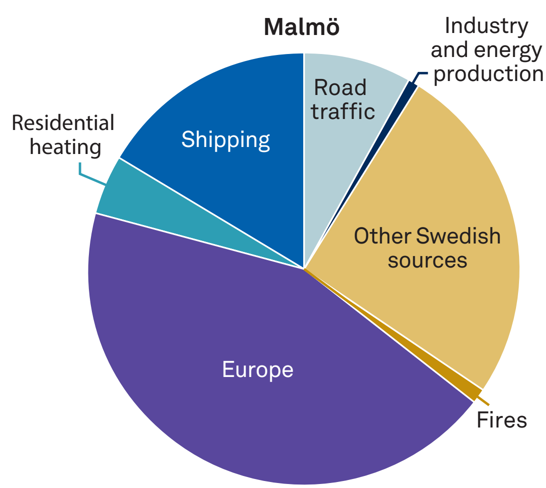


Photo: Getty Images

Volcanic eruptions can cause several types of particle emissions and the ash can spread long distances. In 2010, the eruption of the Icelandic volcano Eyjafjallajökull stopped air traffic in large parts of Europe.

Sometimes particulate mass consists almost exclusively of natural particles – such as sea salt, desert dust, biological particles, volcanic ash and sulphates. In these cases, it is difficult to influence emissions, but modelling can contribute with forecasts to predict high concentrations of matter, which can help mitigate the negative impact of exposure to particles.

Integrated assessment modelling combines the contribution of different emission sources to particulate exposure with other information, such as environmental quality objectives and cost estimates for measures intended to reduce particulate matter and costs associated with exposure. Use of these types of models allows optimising measures so that the necessary environmental improvements can be achieved at the lowest possible cost.

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Further reading

The Convention on Long-range Transboundary Air Pollution (unece.org)

The co-operative programme for monitoring and evaluation of the long-range transmission of air pollutants in Europe (emep.int)

European air quality | Copernicus Atmosphere Monitoring Service (copernicus.eu)

Airborne particles impact our climate

It is well known that the concentrations of carbon dioxide, methane and other greenhouse gases affect our climate. But our climate is also affected by airborne particles. Although particles have an overall cooling effect, particle concentrations in the air need to be reduced due to their impact on human health. Air pollution kills around 7 million people in the world prematurely every year.

Some particles, such as sulphur particles, scatter sunlight so that it does not reach the surface of the Earth, thus having a cooling effect on the climate. Soot particles, on the other hand, absorb sunlight and return it to the surrounding air as heat – so they have a heating effect on the climate. This direct impact on the climate is both due to the chemistry of particles and their size and number.

Particles change how clouds influence the climate

Clouds have a strong impact on our climate. We can feel it immediately when the sun is shaded by clouds. Clouds also reflect outgoing heat radiation, which is why cloud-free nights are often chilly. Cloud droplets form when water vapour condenses on airborne particles. The chemistry, size and number of the particles affect the number of droplets formed in a cloud. The number and size of droplets have a huge part to play in how they scatter sunlight, i.e. how much is reflected and how much is absorbed. So airborne particles have an indirect effect on the climate because the climate impact of clouds depends in part on how particles change the way clouds reflect light.

Methane

Methane is a greenhouse gas because of its strong impact on heat radiation. Chemical reactions in the atmosphere with methane also produce a significant amount of ozone, which is both a greenhouse gas and an air pollutant. Besides health effects, ozone also causes significant damage to various crops, leading to a reduction in food supply. The damage to vegetation also exacerbates climate warming by reducing the carbon sink.

Air pollutants have a significant impact on the climate

Human activities are a huge cause of airborne particles all around the world. Researchers question whether there are any areas of completely unpolluted air left on the Earth. The northern hemisphere's atmosphere is particularly affected, not just by local emissions but also by long-range transport of air pollutants. The Arctic Haze phenomenon during the spring in the Arctic is mainly caused by emissions from Europe and Russia.

Modelling studies clearly show that the increased incidence of air pollutants, particularly from the 1950s to the early 1990s, has dampened global warming caused primarily by rising carbon dioxide concentrations. On the other hand, the subsequent decrease in air pollutants, especially in sulphur dioxide, has contributed significantly to increased global warming. Nevertheless, air pollution still causes significant cooling of the planet (see Figure 1).

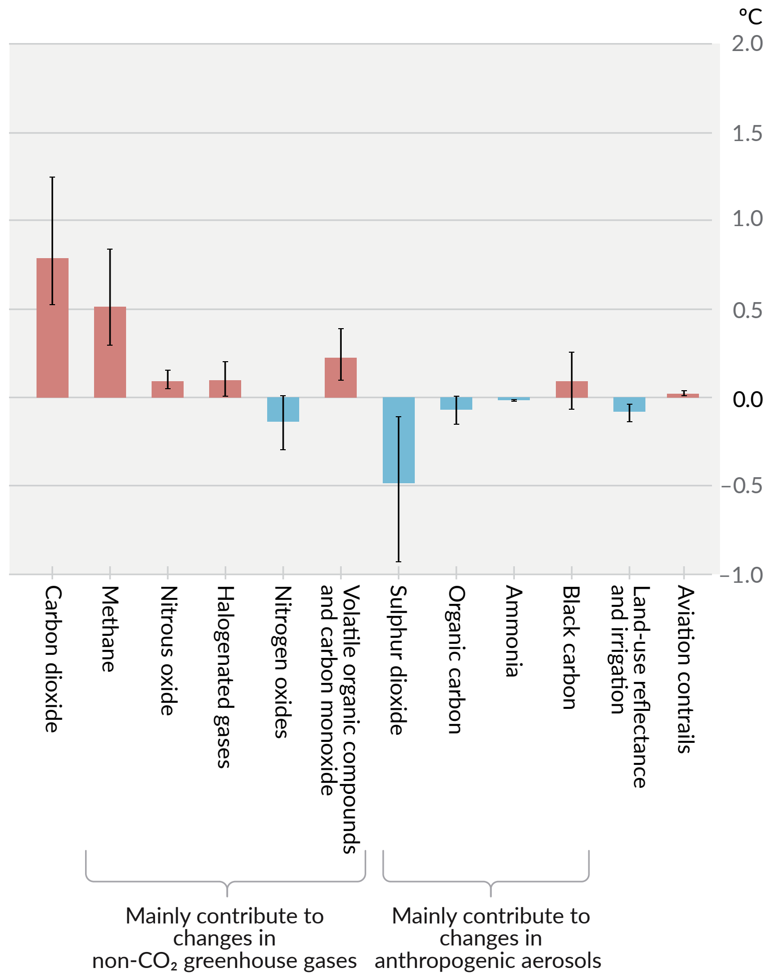
Changing circulation patterns reinforce climate change

Particles have a major impact on how much sunlight reaches and heats our planet. When the amount and distribution of the radiation that heats the entire world changes, this also changes the complex air flow patterns that give us what we normally call "weather", i.e. the temperature variations and precipitation patterns that accompany moving areas of high and low pressure.

The effects of particles on radiation balance are largest in their source regions, i.e. the most populous and industrialised regions, such as Europe. However, temperature changes

Figure 1. Assessed contributions to observed warming in 2010–2019 relative to 1850–1900

Global warming caused by anthropogenic emissions, where heating due to greenhouse gases is partly concealed by the cooling effect of airborne particles. The contribution to warming has been calculated based on the impact of different components on the radiation.



Source: IPCC, Sixth Assessment Report, Working Group 1, The Physical Science Basis, Chapter 6.

areas than in the Arctic. This is because the global flow pattern has changed as a result of increased greenhouse gas concentrations and changes in airborne particle concentrations. More warm air from the tropics and intermediate latitudes is transported up to the Arctic. In addition, there are amplifying effects in the Arctic as a result of increased warming. Sunlight is better absorbed when ice and snow melt away and are replaced by ice-free sea and bare ground, increasing the effects of warming. Changing ground and ice conditions increase the heat insulation effect of clouds during winter. According to the UN climate panel (IPCC), Arctic warming is happening more than twice as fast as global warming in general. More recent summaries of observations indicate that this warming may be as much as 4-5 times faster.

The average annual temperature in the Arctic has increased by about 1.5 °C between 1990 and 2015, of which about 0.7 °C is attributed to rising carbon dioxide concentrations and 0.7 °C from less sulphur dioxide. Reduced soot emissions contribute only to a mere 0.1 °C of cooling.

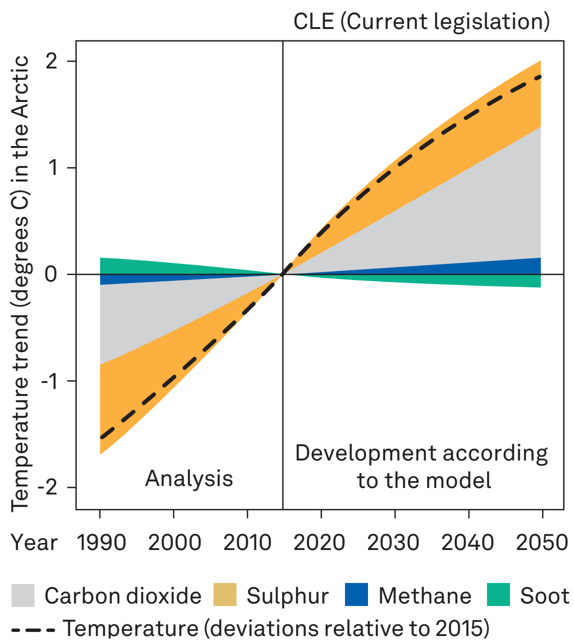
Soot emission reductions are too small to slow the rise in temperature

Soot per kg of emissions has about 4–5 times more impact on temperature than sulphur dioxide, so its relatively modest contribution to slowing the temperature rises in the Arctic is due to the fact that there have only been small decreases in soot emissions since 1990. Emissions of sulphur dioxide from Arctic Council members and observers are estimated to have decreased by about 50,000 kilotonnes (1 kilotonne = 1,000 tonnes) annually between 1990 and 2015, while emissions of soot have only decreased by about 800 kilotonnes per year. This means that the cooling effect of sulphur particles is significantly reduced, which causes the climate to heat, while the relatively small reduction in the warming soot results in only a slight reduction in climate warming. In total, the reductions in sulphur and soot help warm the climate (see Figure 2).

Figure 2. Temperature trends in the Arctic relative to 2015

The figure shows how temperatures have changed in the Arctic due to changes in carbon dioxide concentrations in the atmosphere (in grey), emissions of sulphur (in orange), methane (in blue) and soot (in green). Historically, reduced sulphur emissions have caused as much heating as carbon dioxide.

If agreements and current legislation continue to apply (CLE, "Current Legislation" scenario), reductions in sulphur emissions will contribute an additional 0.4 °C, while increasing methane and decreasing soot will balance each other out.



Source: AMAP report "Impact of Short Lived Climate Forcers".

Photo: Adobe Stock

Climate change, together with growing deforestation, is reducing the Amazon's important role as a carbon sink.

Impact on the Amazon's ecosystem

The Arctic is not alone. The tropics are also affected by the changed pattern of circulation in the atmosphere. The precipitation pattern in the Amazon region has changed, with longer dry periods and higher temperatures greatly affecting the natural tropical ecosystem. The tropical forest transports less water vapour back into the atmosphere, which means less precipitation downstream to the south of the Amazon region. At the same time, carbon dioxide sequestration decreases due to photosynthesis slowing down at higher temperatures. Several studies show that this, together with accelerated deforestation, has led to the Amazon becoming a carbon source instead of an important sink, i.e. more carbon dioxide is now emitted than is stored.

These examples from the Arctic and Amazon show that airborne particles are an important part of an event chain that can significantly change regional climate and its ecosystems far beyond the global mean value. This underscores the importance of minimising their impact on the climate.

Air quality must be improved without further deterioration of the climate

The effects of air pollutants on human health, particularly from particles, is significant. The WHO points out that airborne particles, measured as $PM_{2.5}$, cause the most premature deaths among health hazardous pollution. This makes significant reductions in emissions of particulate matter, like soot, and particle forming gases, like sulphur dioxide, hugely important.

As sulphur dioxide significantly contributes to $PM_{2.5}$, it must be reduced despite the fact that this will have a warming effect on the climate. This reduction therefore needs to be linked to reducing warming particles, like soot, to minimise the

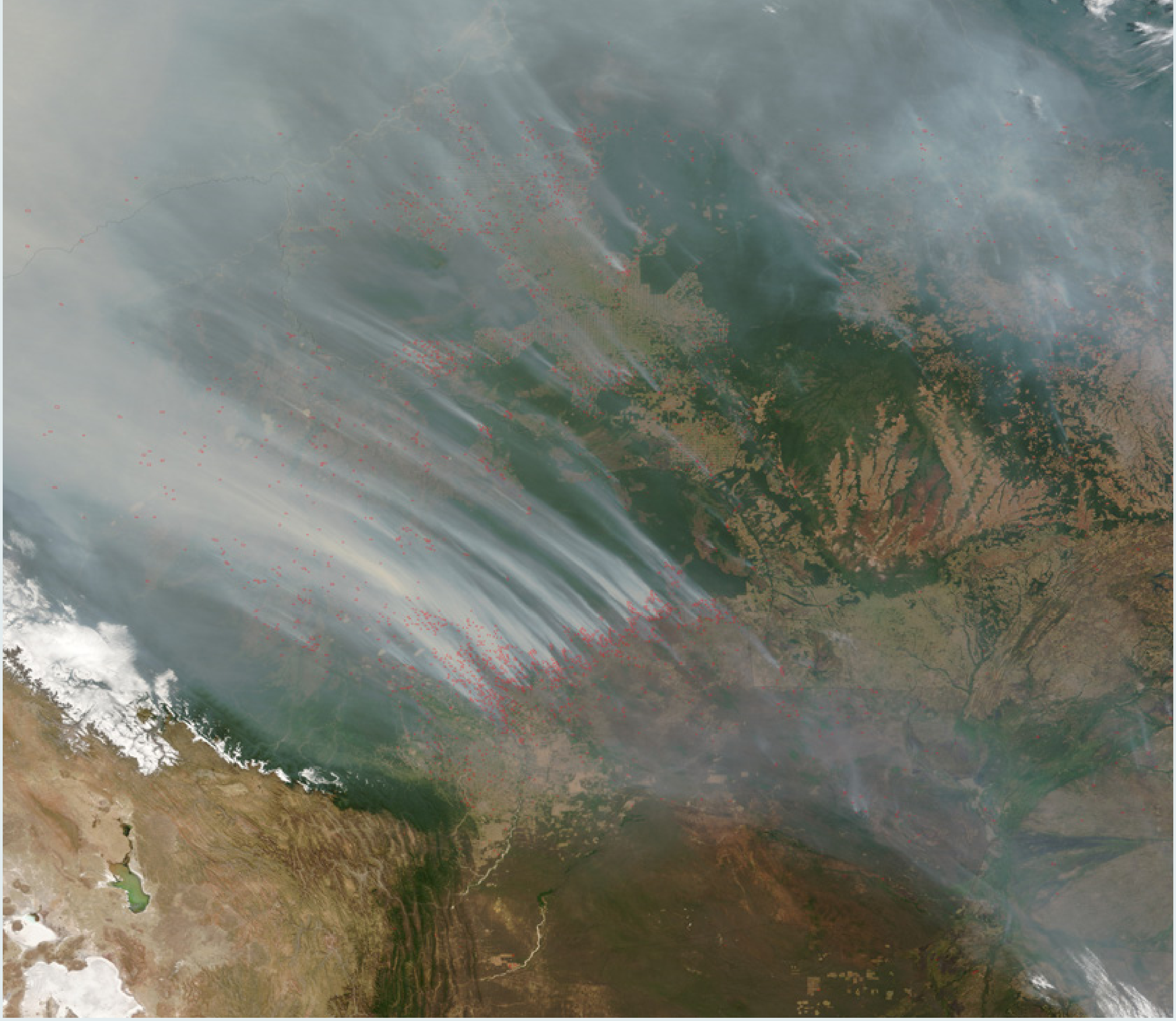


Figure 3. Satellite image of smoke from deforestation in the Amazon

The fires are visible as red dots.

Source: NASA image courtesy Jacques Descloitres, MODIS Rapid Response Team, Goddard Space Flight Center.

As the climate warms, forest fires tend to increase

Forest fires cause very high emissions of particles. The deforestation in Amazonas is well known and has a strong impact on air quality. In recent years, observations have shown an increasing incidence of forest fires, especially in the boreal forest, that is the belt of coniferous forest that extends through Eurasia via Siberia and on through Canada. In recent years, concentrations of particles from these fires in Canada and Siberia have reached the same concentrations as those found in the Amazon caused by the fires associated with deforestation. These huge fires are caused by prolonged dry periods and high temperatures. In addition to carbon dioxide, particle emissions from these are largely soot, organic carbon and ozone-forming gases. The increasing incidence of forest fires causes a concerning amplification of climate warming.

climate effect. Reducing soot is also necessary since these particles have significant adverse health effects. A soot particle warms about 4–5 times more than a sulphur particle cools, but current sulphur emissions are about ten times greater than soot emissions. This means that the climate effect of a 100 per cent reduction in soot emissions only compensates for a 50 per cent reduction in sulphur emissions. Further reducing sulphur requires a reduction of other climate-warming air pollutants, such as methane. The sharp reduction in sulphur emissions over the last 30 years, without reducing soot and methane, has caused almost as much warming as the increase in carbon dioxide (see Figure 2, page 78).

A balance is needed between heating and cooling effects

Reducing emissions of particles and gases that produce ozone is important because of their significant impact on our health. Annually air pollutants, mainly $PM_{2.5}$, cause approximately 7 million premature deaths globally. Reductions in emissions are vital to achieving several of the UN's global Sustainable Development Goals. HOWEVER, addressing accelerating climate warming requires balancing heating and cooling components so that future improvements in air quality are climate neutral. Emissions of soot and methane must be substantially reduced to compensate for the warming resulting from a reduction in sulphur dioxide.

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Improved climate scenarios require better knowledge

Particles have a significant impact on the climate, but there is still a lack of knowledge about the various climate-affecting processes in which atmospheric particles play a part. In particular, the impact of particles on clouds influence the models' ability to describe how the climate will develop. In its 2021 report, the IPCC identifies the interaction between particles and clouds as the most important thing to study to reduce the uncertainty of climate projections. Particles, through their impact on clouds, also impact the intensity and periodicity of precipitation.

Recent research has clearly shown that greenhouse gas emissions must be drastically limited to halt climate warming and that air quality must be improved by substantially reducing ambient air particle concentrations. To prevent these measures from being counter-productive, the heating and cooling components of air pollutants must be reduced through climate-neutral measures.

Further reading

IPCC, 2021: The Physical Science Basis. Summary for Policymakers (ipcc.ch)

AMAP, 2021: Impacts of short-lived climate forcers on Arctic climate, air quality and human health. Summary for Policy-Makers (amap.no)

Artaxo, P., et al., 2022. Tropical and Boreal Forest – Atmosphere Interactions: A Review Tellus B, 74(1), pp. 24–163 (tellusjournals.se)

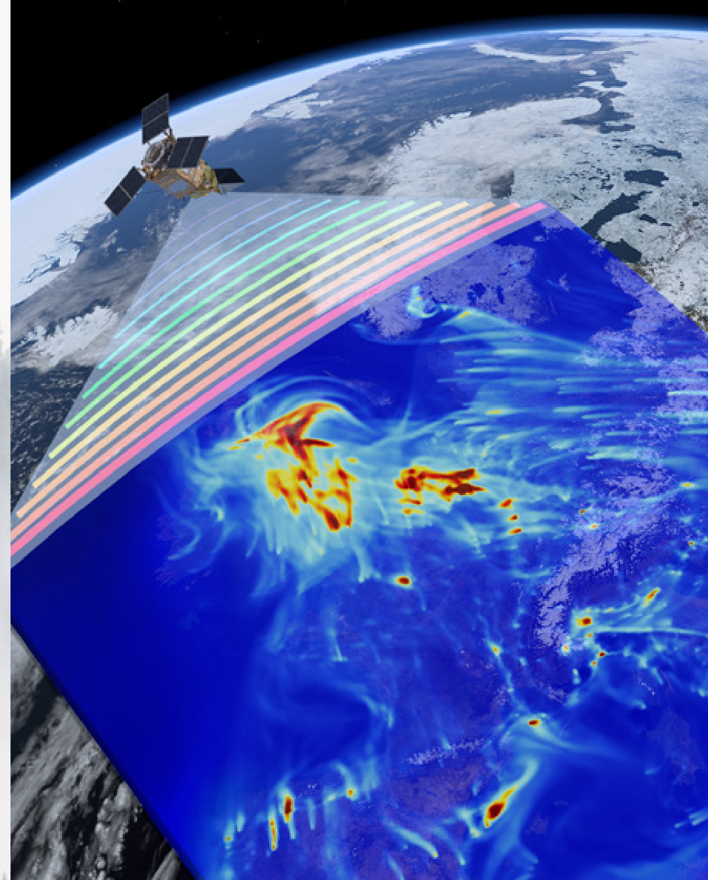
Lewinschal, A, et al., 2019. Local and remote temperature response of regional SO2 emissions, Atmos. Chem. Phys., 19, 2385–2403 (copernicus.org)

Sand, M. et al., 2020. Surface temperature response to regional black carbon emissions: do location and magnitude matter?, Atmos. Chem. Phys., 20, 3079–3089 (copernicus.org)

Dispersion models increasingly important as forest fires increase

The forest fires in the summer of 2018 were by far the most extensive in Sweden in modern times. They covered 25,000 hectares (about 36,000 football pitches), which is almost ten times the average for the 2000s. The extremely dry and hot weather during the summer of 2018 was a wake-up call that climate change can contribute to a higher risk of forest fires in Sweden. It pointed to the need for a national forecasting system for wild fire particles, combined with public advisories of high concentration levels.

Forest fires can release large amounts of atmospheric particles that are dangerous to human health.



Air quality forecasts in Europe – CAMS

Copernicus Atmospheric Monitoring Services (CAMS) is part of EU's Earth observation system. CAMS presents daily forecasts for the dispersal of air pollutants, such as particles ($PM_{2.5}$ and PM_{10}), ground-level ozone and nitrogen oxides, and forecasts of particles from specific sources such as forest fires.

The forecasts are made available with a focus on Europe but also for the entire planet. The forecasts are based on a combination of chemical transport models, ground-based measurements and satellite observations. Nine of the leading chemical transport models in Europe are used for the European forecasts, including the EMEP MSC W and the MATCH model (developed by SMHI). Estimates of daily emissions from forest fires are produced based on satellite measurements and are used by the models to describe the transport of wild fire particles.

Source: European air quality | Copernicus Atmosphere Monitoring Service. (copernicus.eu).

Forest fires can produce large amounts of smoke containing small particles that are harmful to health. The concentrations are highest near the fire, which can affect firefighters, but the particles can also affect residents in areas reached by the fire plume. Today, we have forecasts for particle dispersion from European forest fires, but these lack sufficiently high resolution for use nationally. Technical solutions exist to enable national preparedness that would allow us to protect human health.

How can we describe the dispersion of wild fire particles?

Many factors affect smoke and particle emissions from a forest fire, including weather, tree species and soil conditions in the forest. The smoke from the forest fire is dispersed with the winds, further away with stronger winds and shorter distances with precipitation or less wind.

There are global daily estimates of emissions from wild fires. These are produced through advanced calculations based on satellite observations. These estimates can be combined with weather forecasts using advanced dispersion models to describe how the particles from the fires are dispersed and transformed in the atmosphere and ultimately deposited. This type of calculation is done within the CAMS operational air pollution forecasts for the whole of Europe (see fact box).

Jämtland-Härjedalen 2018

In addition to forecasts, calculations can also be made of historical levels and human exposure to particles from forest fires. One such study calculated concentrations of air pollutants from the 2018 forest fires (see Figure 1) to estimate health impacts of wild fire particles.

Figure 2 shows population exposure to $PM_{2.5}$ in the municipality of Östersund during the summer of 2018 (the dark blue line shows exposure caused by forest fire particles). The dispersion of forest fire particles and the emission, transformation and transport of other particles and air pollutants were calculated hour by hour, both in a wider area covering all of Europe and in a smaller area covering central Sweden at a finer resolution.

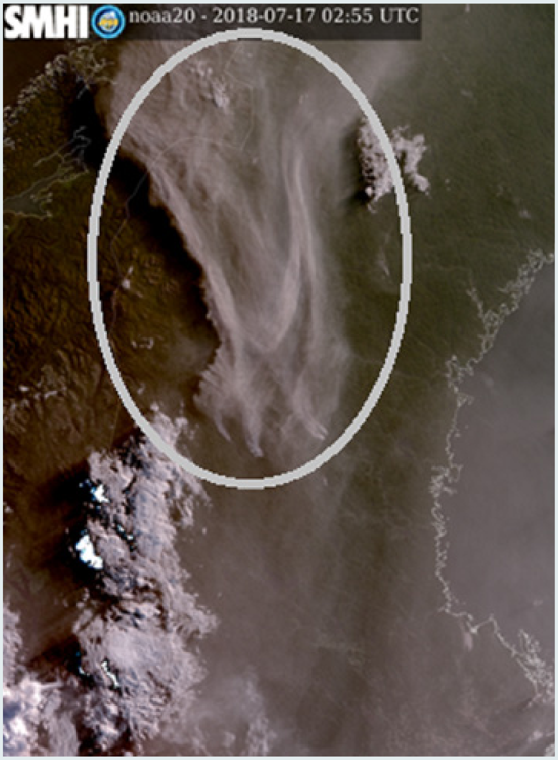


Figure 1. Smoke plume from forest fires in Jämtland-Härjedalen in 2018.

The grey circle is around the main part of the fire smoke plume (grey colour), the other white and grey shapes include different types of clouds and coastline.

Source: Swedish Meteorological and Hydrological Institute (SMHI).

Health impacts of wild fire particles

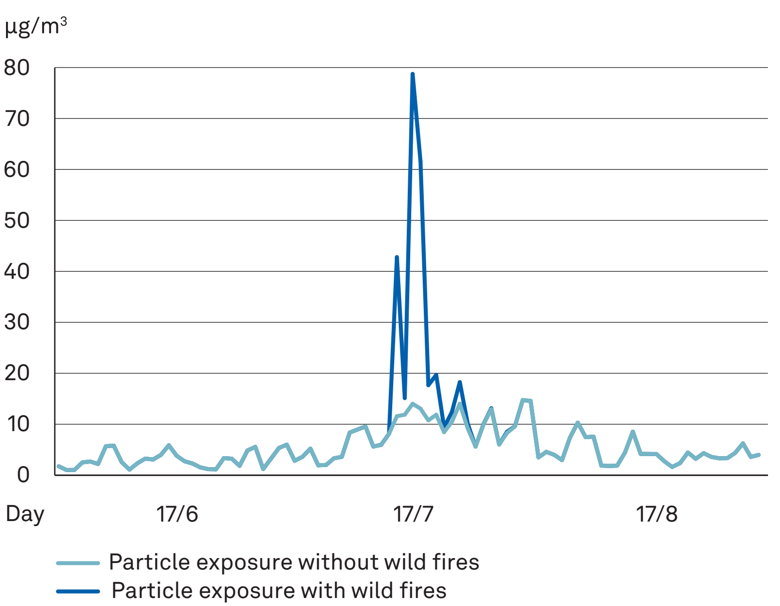
Air pollution from forest fires both has acute adverse health impacts for sensitive individuals, within hours or days, and contributes to the onset of disease and premature death due to a higher long-term exposure.

A health impact assessment estimated that smoke from wild fires annually causes 339,000 premature deaths globally. An international epidemiological study of the acute impact of wild fire particles on the daily number of deaths in 749 cities calculated that roughly 0.5 per cent of all deaths are caused by $PM_{2.5}$ from forest fires. There are many studies on the acute effects in the respiratory tract, primarily an increase in the daily number of emergency visits and hospital admissions for asthma and respiratory problems, while the evidence on acute cardiovascular disease is weaker.

Countries like the US and Canada have used the correlation between wildfire-related $PM_{2.5}$ concentrations and acute health effects to produce air quality indices for wildfire smoke and a system of advisories or warnings connected to risk categories for these indices. These are communicated by authorities, media and online. The concentration limits applied in the risk categories varies. In the state of Montana, the advisory to limit outdoor activities for sensitive individuals starts at one hour outdoors when $PM_{2.5}$ concentrations are above 12 micrograms per cubic meter, while the corresponding threshold in other places can be more than twice as high.

Figure 2. Maximum $PM_{2.5}$ concentration in Östersund in 2018

Modelled population exposure for the daily maximum $PM_{2.5}$ concentration in the municipality of Östersund in the summer 2018. Dark blue line shows the particle exposure including wild fire emissions. The lower curve (light blue) shows the exposure of the population without wild fires. The resulting exposure will vary depending on the location of the fire compared with the municipality and where the smoke plume moves. The highest exposure to fire smoke particles was during the summer of 2018 in the municipalities of Berg and Härjedalen with a different time variation.



Source: Swedish Meteorological and Hydrological Institute (SMHI).

Dispersion of smoke from forest firest in the northern hemisphere

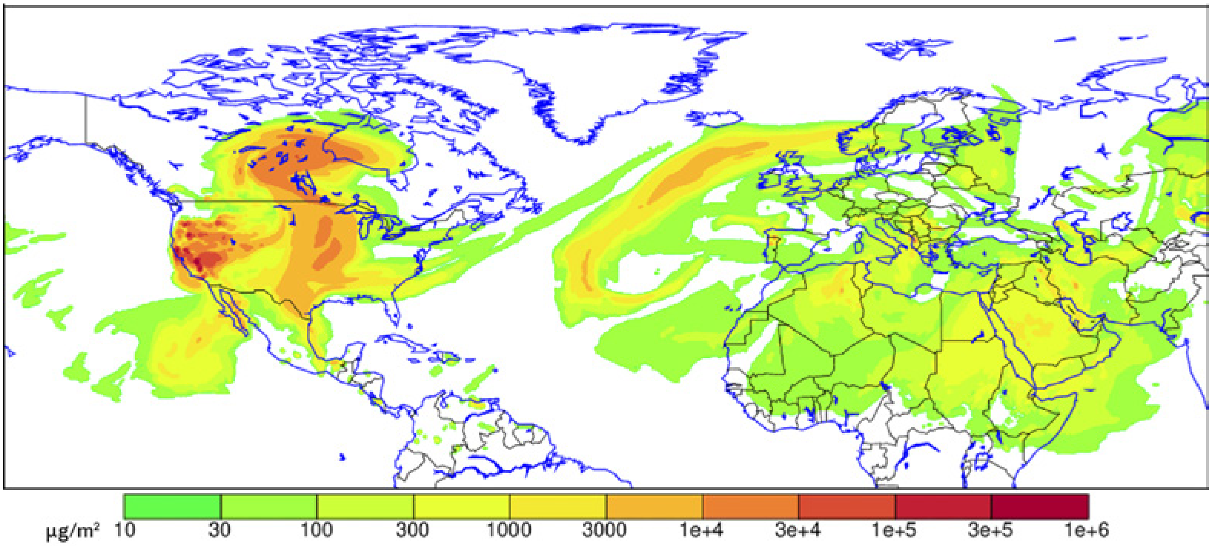
Forest fires occur every year with varying extent and spread over large areas of the globe. At high latitudes, wide-spread fires often occur in the Arctic (especially northern Russia, Alaska and Canada). Other areas with recurring fires include Africa, Australia, North and South America, Eastern and Southern Europe, and the rest of Russia.

These fires locally contribute to poor air quality, but fires in the northern hemisphere can also contribute to elevated levels of pollution in background air in Sweden. Concentrations can be so high that sensitive individuals should avoid strenuous outdoor activities. This can result from wind transporting polluted air from other parts of Europe and by transport in the free troposphere to Sweden from other parts of the world (e.g. from wild fires in California, see Figure 3). The CAMS operational system can be used to identify transport events and contribute to a preparedness system protecting human health.

One such transport event took place in September–October 2020. A combination of dust from a desert storm and particles from forest fires in Ukraine and southern Russia caused exceptionally high particulate concentrations in northern Europe. In this type of event, CAMS forecasts should be combined with satellite and ground-based observations for a better understanding of what is happening, to monitor concentrations and to provide public advisories on protecting human health. Modelling studies can also be conducted in retrospect, to improve the understanding of transport events and to improve systems for identifying the highest concentrations and providing health warnings.

Figure 3. Total column of $PM_{2.5}$ from forest fires, 20 September 2020, 12:00 UTC

$PM_{2.5}$ from wild fires, added vertically in the atmosphere (total column) on 20 September 2020. The picture shows the dispersion of particles from fires in California across the North American continent and the North Atlantic. Fires in other parts of the world, including Africa, also contribute to the dispersion picture. The image is based on dispersion modelling of concentrations in the atmosphere with the MATCH model and emission data of fire smoke particles based on satellite measurements.



Source: Swedish Meteorological and Hydrological Institute (SMHI).

Photo: Adobe Stock

Air quality forecasts can be used for warnings and advisories connected to high particle concentrations, which can help protect human health.

Future needs

A higher resolution national system for forecasting air pollutants could provide forecasts of particles from forest fires in Sweden and indicate what areas need measures to protect human health. These measures could include advisories based on threshold levels of particle concentrations, such as avoiding strenuous outdoor activities above a specific concentration and staying indoors and turning off ventilation at higher concentrations. Health advisories for high concentrations of particles could be introduced in Sweden for long-range transport events based on the CAMS forecasts and ground-based measurements. It is important to make use of available technological solutions to avoid adverse health consequences.

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Further reading

Air Quality and Your Health. Recommendations from The Montana Department of Environmental Quality (mt.gov)

GWIS Global Wildfire Information System - Current Situation (europa.eu)

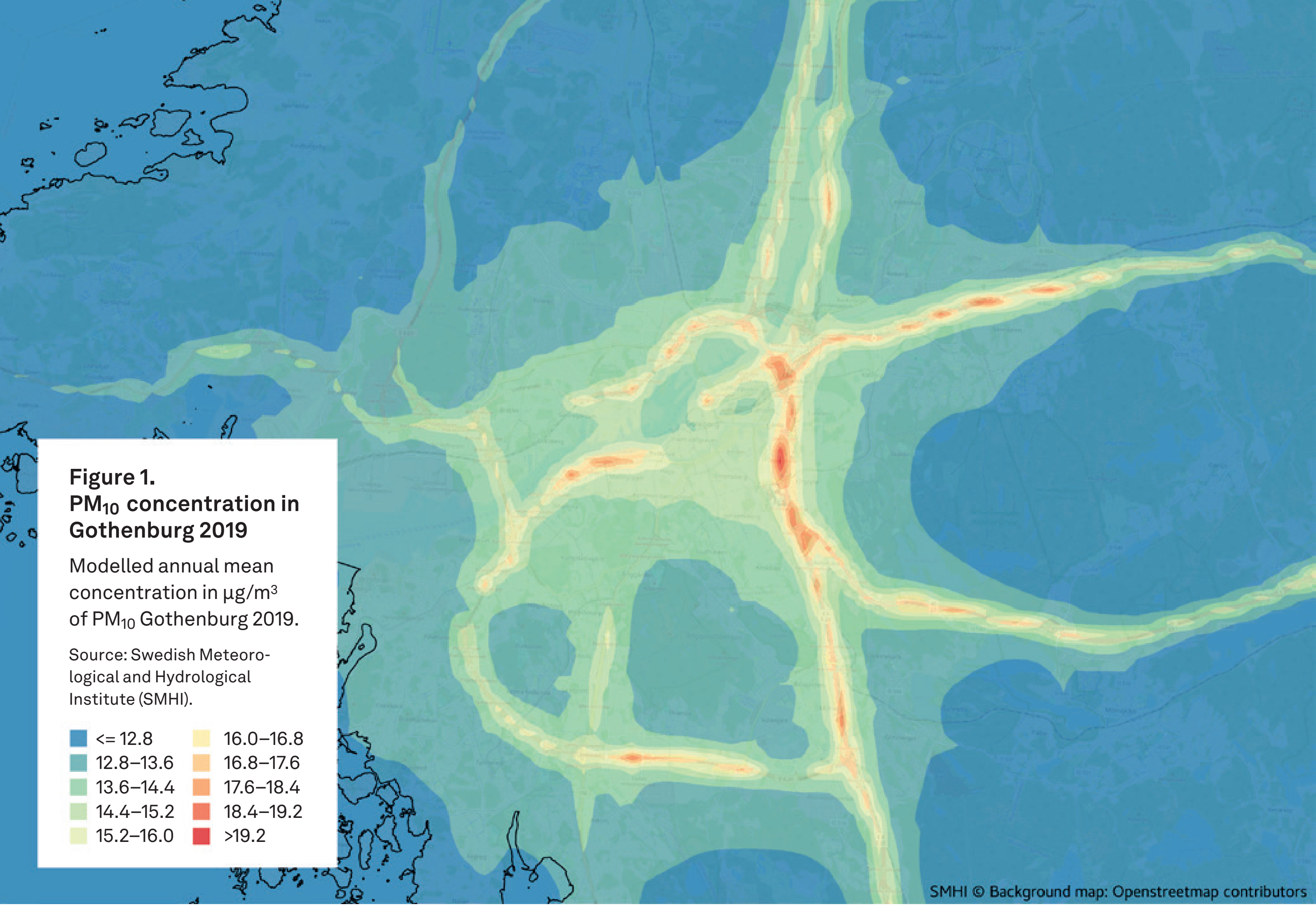


Figure 1.
PM_{10} concentration in Gothenburg 2019

Modelled annual mean concentration in µg/m³ of PM_{10} Gothenburg 2019.

Source: Swedish Meteorological and Hydrological Institute (SMHI).

How to use modelling to improve urban air quality

The air pollutants , in particular particles, in the urban air we breathe are a public health problem. Improving air quality is in everyone’s interest, but implementing effective measures requires an understanding of both where the emissions come from and how they spread. Combining measurements and modelling provides a good knowledge base to take actions to achieve cleaner air.

Air quality in urban areas is influenced by many factors. For example, background concentrations and sources of local emission vary across the country. Meteorology and building design can also have a large impact on pollution concentrations.

Particle measurements provide a good indication of air quality at the location of the measurement station but concentrations can differ greatly in different places within the same city. Dispersion models can therefore play an important role for mapping air quality over a larger area and for calculating the effects of different measures.

Dispersion models in urban areas

Different dispersion models can be used in urban areas, and each has different strengths and weaknesses. With densely built areas, air circulation is reduced and dirty air is not ventilated out of street canyons as effectively. Local-scale dispersion models can describe the effects of buildings on ventilation. These models provide valuable insights for urban planning and air quality monitoring, but they require high-quality input data to provide reliable results. This input data include:

- geometries of the site (building heights, road width, etc.),
- weather data (wind direction, wind speed, temperature and precipitation) and
- emission data or data for emission estimates. Traffic data is vital for modelling road traffic, including the number of vehicles on the roads, the proportion of buses and other heavy duty vehicles (HDV), and information on road maintenance/cleaning.

In addition to input data, models need to be validated with qualitative measurements of air quality to ensure they reflect reality.

How can dispersion modelling support efforts to improve air quality?

- Mapping air quality improves understanding of air quality over the entire urban area.
- Combining measurements and modelling provides a solid knowledge base from which to work.
- Source apportionment defines which emissions affect concentrations and to what extent.
- Modelling allows the evaluation of different measures for improving air quality so that the most effective measure is chosen for the relevant location.

The most important local emission sources

Road traffic is a major local source of emissions in our cities. For particles, emissions occur both from vehicle exhaust gases (mainly smaller particles, $PM_{2.5}$) and from road wear from friction (mainly larger particles, PM_{10}). Studded tyres contribute to increased wear of the road surface. Sanding and salting also contribute to road dust. In the spring, especially, there is a risk of high particle concentrations when accumulated road dust are resuspended in the air from dry roadways.

Residential wood burning is a local, sometimes overlooked emission source. This is especially true for old wood boilers, but bad burning habits of using wet wood logs and incomplete combustion also cause particle emissions of substances harmful to health. Urban areas without developed district heating generally have higher emissions from residential wood burning.

In addition to road traffic and residential heating, other local emissions can be significant. Shipping can contribute if there is a port or major waterway nearby. An industry, local boiler plants or other combustion facilities can also have a significant impact locally.

We can take effective measures only once we understand which emission sources contribute the most to particle concentrations. In cases where environmental quality standards are exceeded, the Swedish Environmental Code (Chapter 5, section 7) requires the implementation of an air quality plan. When developing an air quality plan, a source apportionment is drawn up that describes which emission sources contribute to the elevated concentrations. Dispersion modelling is a cornerstone of source apportionment.

Measures for reduced particle concentrations

Dispersion models are very good tools for evaluating how different measures are expected to affect particle concentrations. First, a base scenario is made using current conditions and then different scenarios can be tested to evaluate which measures have the greatest effect on particle concentrations.

An example scenario for simulating particle concentrations (PM_{10}) in street canyons has been produced with the help of SMHI's SIMAIR air quality system. This example uses the road Kungsgatan in Norrköping

Photo: Mostphotos

Kungsgatan in Norrköping, Sweden. The street canyon used for the calculations is at the top of the picture after the traffic light.

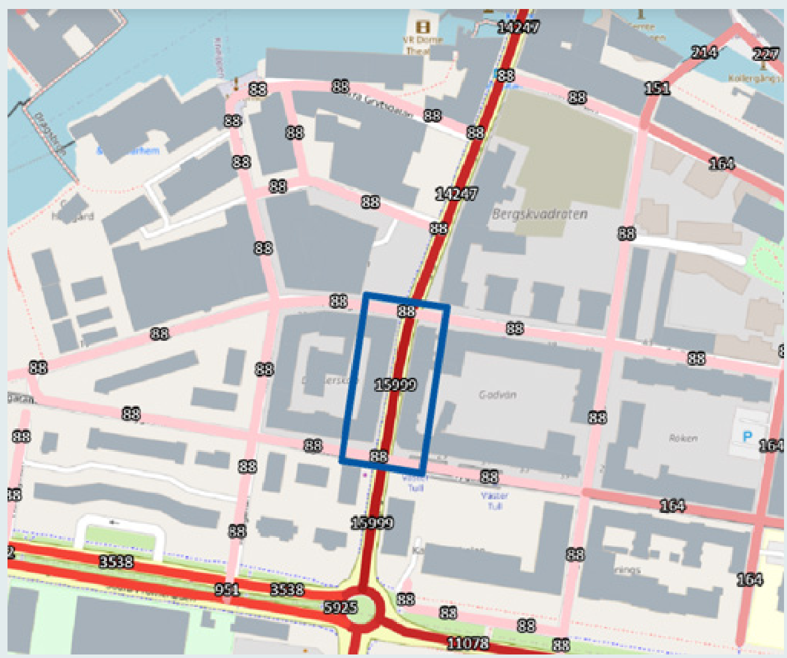


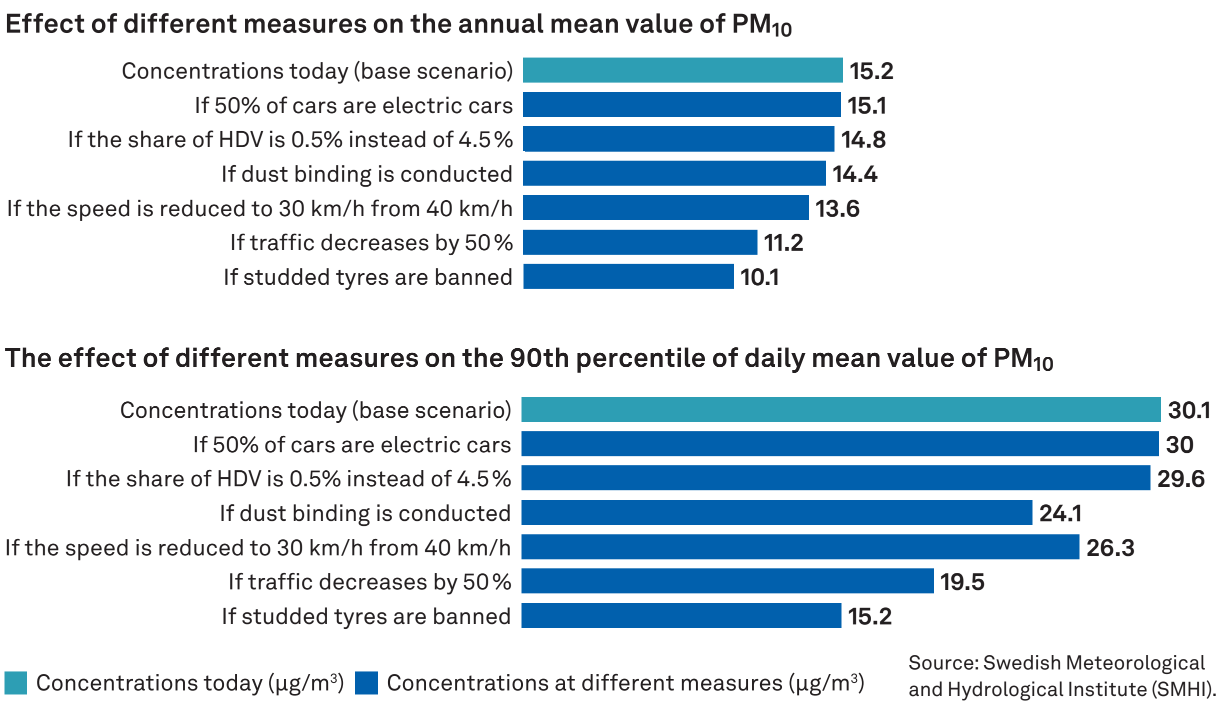
Figure 2. Dispersion modelling in central Norrköping

Map of central Norrköping from the SIMAIR air quality system, where the numbers on the roads indicate annual daily traffic (ADT). Kungsgatan is north from the roundabout. The selected traffic canyon where the calculations were performed is marked with a blue box.

Source: Swedish Meteorological and Hydrological Institute (SMHI).

Figure 3. Effect of different measures on PM_{10} concentrations

Annual mean value and 90th percentile of the daily mean value (i.e. the 36th highest daily mean value during a calendar year) for calculated concentrations of PM_{10} on Kungsgatan in Norrköping. The bars show how the concentrations differ for several scenarios simulated with SIMAIR.



Source: Swedish Meteorological and Hydrological Institute (SMHI).

(see Figure 2). The calculations were made in a narrow street canyon between two tall facades and with annual daily traffic of nearly 16,000 vehicles. In SIMAIR, the user can change the various parameters that provide input data for the calculations. Six separate measures to improve air quality were investigated, and the calculated concentrations were compared with the base scenario.

The example measures are shown in Figure 3, where the annual mean value and the 90th percentile of the daily mean value (i.e. the 36th highest daily mean in a calendar year) are presented for PM_{10}. The bars show total concentrations, i.e. regional (from Europe and the rest of Sweden), urban (from the urban area/city) and local contributions from the road in question combined.

Which dispersion model should I use?

There are many models with varying complexity and areas of use. Visit Reference Laboratory for Air Quality - Modelling for model selection support. www.smhi.se/reflab

SIMAIR provides the user with information on what percentage comes from local effects. In this case, the local contribution from the road is roughly 50 per cent of the annual mean value, i.e. roughly 8 micrograms per cubic meter.

Studded tyre bans and reduced traffic are the most effective measures

The calculations show that banning studded tyres is the most effective measure for lowering PM_{10} concentrations. Studded tyres, in particular, are a well-known cause of PM_{10} emissions, because the studs cause wear on the road surface, releasing particles. In the base scenario, studded tyre use is assumed to be at 66 per cent and in the measure scenario at 0 per cent. This measure is even more effective than reducing traffic by 50 per cent, which is the second most effective measure in the example.

Lowering road speed, in this case from 40 km/h to 30 km/h, would also contribute to lower levels, as lower speed causes less road wear and less resuspension of road dust in the air.

A couple of measures that have a smaller effect on the annual mean concentrations are reduced proportion of heavy duty vehicles (HDV) and dust binding. The percentage of heavy duty vehicles is 4.5 per cent in the base case and 0.5 per cent in the measure scenario. However, the effect of this measure is more significant when looking at exhaust particles or nitrogen oxides.

Dust binding has the largest effect in the spring

Dust binding has a larger effect on the daily mean value (90th percentile) than on the annual mean value. This measure is estimated to reduce the annual mean value by less than 1 microgram per cubic metre, but a reduction of 6 micrograms per cubic metre is seen when looking at the daily mean value (90th percentile). This is because dust binding is effective in late winter/early spring, when the roads are snow-free and dry and vehicles still use studded tyres to a large extent. Days with high PM_{10} concentrations mainly occur during this period, and concentrations can be reduced by applying dust binding agents. The method involves coating the roads with moisture so the roads do not dry up. The coating is in the form of a salt solution that affects the water vapor pressure.

More electric cars do not reduce coarse particles

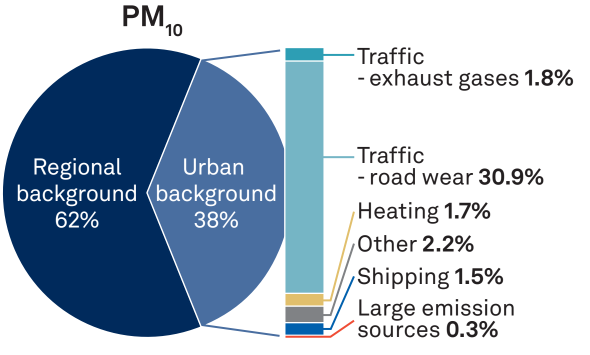
One measure that has practically no effect on PM_{10} concentrations is more electric cars. In this scenario, the share of electric cars was increased from 1.1 per cent to 50 per cent of passenger cars. As long as electric cars also use the same proportion of studded tyres, emissions of PM_{10} are nearly unchanged. Potentially, the emissions of road wear particles could even be greater from EVs, as they are generally heavier due to their batteries.

Photo: Adobe Stock

Banning studded tyres is the most effective measure for lowering PM_{10} concentrations.

Figure 4. Source apportionment of concentrations contributes to an improved understanding

Modelled distribution of concentration contributions from different sources at an urban measurement station in Gothenburg. The diagram on the left is for the annual mean value of PM_{10} and the one on the right is for $PM_{2.5}$. The urban contribution of particles is also apportioned to different emission sources within the city (in the bar charts on the right). The clearest difference between source apportionment for PM_{10} compared with $PM_{2.5}$ is that wear particles make up a larger part of PM_{10}. Particles from road wear mostly consist of coarse particles, while particles from combustion (e.g. car exhaust and wood smoke) consist almost exclusively of smaller particles (<2.5 µm).



Source: Swedish Meteorological and Hydrological Institute (SMHI).

This causes more friction on the road surface, a parameter that SIMAIR does not currently consider. While emissions of exhaust particles decrease with an increased proportion of electric cars, PM_{10} concentrations do not drop significantly because coarser particles from road wear account for a large part of the mass of PM_{10}.

The lack of effect due to increased electrification of the car fleet in the calculation above is a clear example of how important it is to understand which emission sources contribute to particle concentrations.

In summary, dispersion modelling can be used to investigate policy instruments and measures before they are introduced so that we can choose appropriate measures based on effect, cost and other impacts. Dispersion models are an important piece of the puzzle in effectively improving air quality.

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Further reading

Reference Laboratory for Air Quality – Modelling. Information on dispersion models, input data and measures (smhi.se)

Air webb - air quality services for visualising and download of Swedish air quality data (smhi.se)

Segersson, D. et al. (2021). Near-Source Risk Functions for Particulate Matter Are Critical When Assessing the Health Benefits of Local Abatement Strategies (mdpi.com)

The dream of a particle-free society

Air pollutants pose one of the greatest environmental risks to human health. Particulate matter is the pollutant that has the strongest link to adverse health effects and all concentration levels are harmful to health. A completely particle-free society is desirable but would probably be difficult to achieve.

If we were to meet the Swedish Clean Air environmental quality objective in our urban areas, we would see major gains for public health. However, this represents a huge challenge and requires significant changes to our society. There are three ways of reducing the health impact of particulate matter in the air: reducing emissions, reducing air pollutant concentrations and reducing human exposure. This article focuses on larger cities where many people are exposed to particles.

Measures to reduce emissions

The fastest and most effective way to reduce particulate matter levels in the air is to reduce emissions. Transport is the main cause of particulate emissions in urban environments, mainly due to wear of the road surface. Other sources that contribute to particle emissions include tyre and brake wear, exhaust emissions from road traffic and shipping, and wear from rail traffic. As it is technically very difficult to reduce the amount of wear particles, we need to limit road transport. Creating good accessibility while having fewer vehicles on the roads requires us to develop a city in which we are close to everyday needs – that schools and preschools are close to homes and that it is easier to coordinate deliveries.

Transportation in the city needs to largely be in the form of walking and cycling, supplemented by an attractive and well-functioning public transport system. So, these traffic types need to be given more space in cities and in urban planning. Walking and cycling have great potential to replace short car trips in our urban areas. Offering wide and generous pathways and cycle paths in healthy environments serves important functions, both for reducing emissions and for reducing exposure.

Light rail in urban setting.

Source: Målbild Koll2035 – public transport for the backbone networks of Gothenburg, Mölndal and Partille.

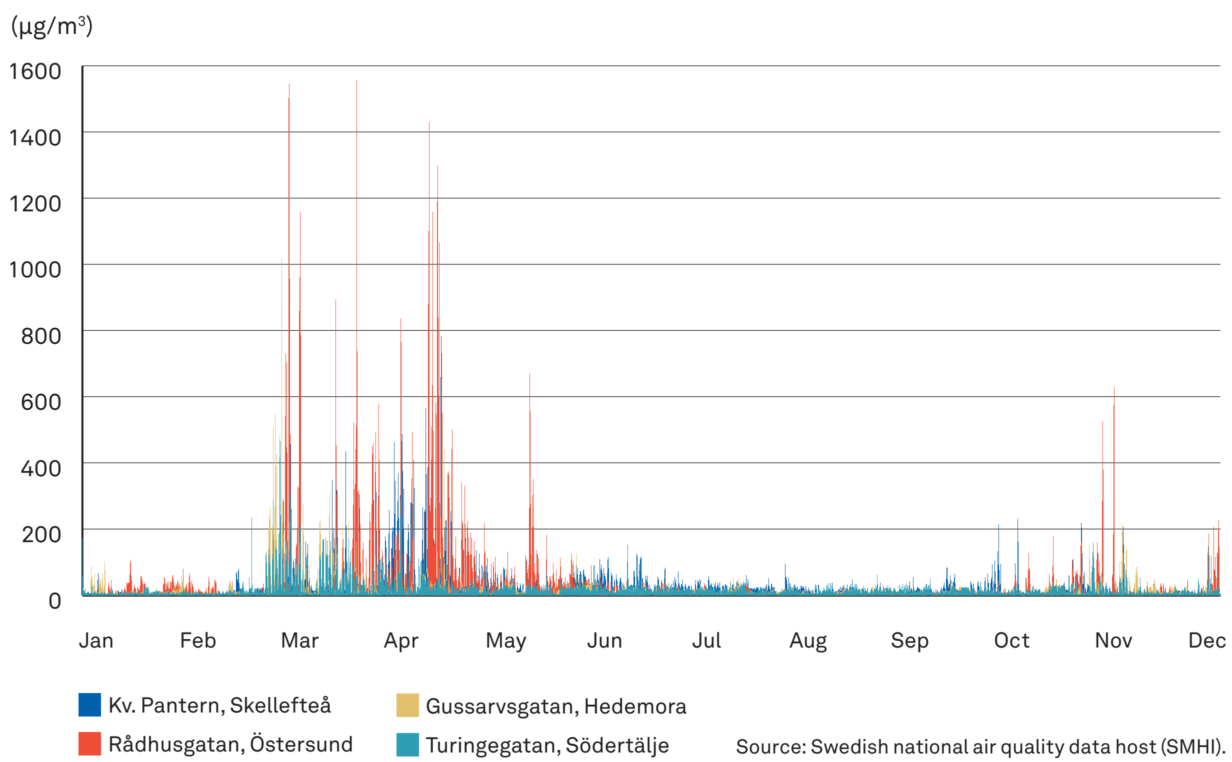
Bicycles can also be used for the delivery of small goods, pickup of waste or for transportation assistance. This has been tested in various cities in Sweden.

An important planning challenge is car parks – numbers, location and what parking should cost. There are benefits to reducing parking standards (i.e. local authority planning regulations for car parking for new builds or rebuilds, often described in terms of number of car spaces per flat, per employee or per square metre of building space) when expanding our cities. This allows more flats in the same area at a lower cost per flat. It should also be easy and safe to park your car along the edge of central urban areas close to crucial hubs for public transport, cycling and walking into the city centre.

Swedish cars use studded tyres during the winter, causing around 15 times more wear on the road than non-studded tyres. Every spring, when the road surfaces dry up and wear particles are resuspended into the air, environmental quality standards are exceeded in many cities in Sweden (see Figure 1). Asphalt with relatively large and hard stones is used in Sweden to reduce wear. The disadvantage of larger stones is that they make the road surface uneven, resulting in higher noise levels.

Figure 1. Hourly mean value of PM_{10} in Skellefteå, Östersund, Hedemora and Södertälje

Measured concentrations of PM_{10} in 2021 on four streets in Sweden. The results show that high levels are more common March–May than in the rest of the year. Hourly mean values, in particular, can reach very high concentrations. The Environmental Quality Standard for PM_{10} is for daily and annual mean values.



Source: Swedish national air quality data host (SMHI).

Photo: Unsplash

Densification of urban areas can lead to increased air pollution concentrations, because pollution remains in the street longer. Open streetscapes, such as detached buildings, are best for good air quality.

Development of materials and road paving is ongoing. One example is porous asphalt, with cavities between the stones, which allow water and wear particles to pass through the surface. This reduces the resuspension of particles into the air and dampens noise levels around the road.

Measures to reduce concentrations

These days, we build our towns and cities much more densely than before. This increased density reduces travel and transport requirements, with shorter distance between people, and public transport can be used more efficiently. However, density poses several challenges, including fewer green areas, less sunlight and poorer air quality. Narrow streets with high rows of buildings result in poorer mixing of the air, which means that pollution from traffic remains in the street canyon and concentrations are high (see Figure 2). Our desire to have vibrant streets with shops, outdoor cafés and an active public life increases exposure to harmful levels of air pollutants.

Figure 2. Traffic pollution remains in the air

Air carrying pollution often swirls along streets and remains in the area.

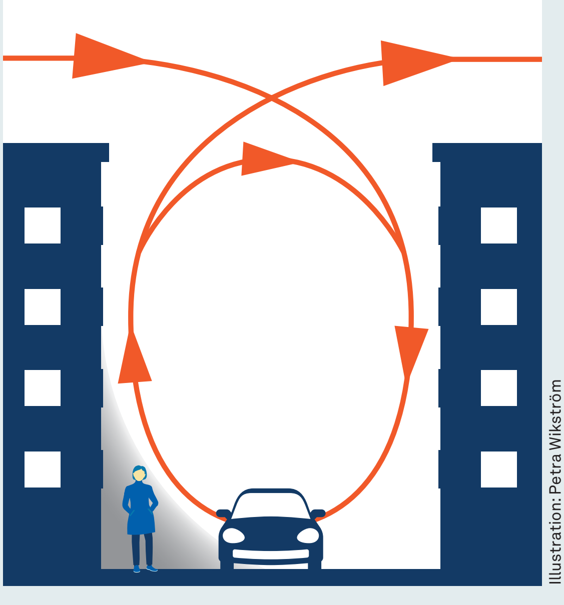


Illustration: Petra Wikström

Virtually any type of increase in density along a street results in increased levels of air pollution, even if emissions are kept the same. Studies have shown that if an open street with sparse buildings is replaced by rows of tall buildings, air pollutant concentrations can increase several fold. This makes it important to design buildings in a way that minimises the negative effects of densification.

Good air quality requires an open street plan with detached buildings that allow good air flow through the street. However, an entirely open street plan is rarely when it comes to reducing noise pollution, which instead benefits from enclosed blocks with quiet courtyards. A completely enclosed street plan may have low particle levels in the courtyards but is also the option that results in the highest concentrations along the street. A compromise may be to create several openings in the closed structure that increases air flow and lower concentrations slightly along the street. Studies have also shown that a varied building height can have a positive effect on air quality due to increased mixing of cleaner air along streets. Another possibility is to concentrate traffic to a street on one block and use buildings to prevent polluted air from spreading into the settings we want to protect. Housing and schools can be located in the protected areas.

Increasing the amount of vegetation in the city can be an attractive way of improving air quality. When polluted air passes through vegetation, some of the particles may deposit on vegetation. Every autumn, when the plants lose their leaves, a certain amount of deposited particles follow with them and are transported away with the leaves. Some of the particles can also be washed off by rain and end up in stormwater. Increased vegetation also provides comfort, shade and increases humidity. With increased humidity, particle concentrations are reduced because the moisture binds dust to surfaces. Studies have shown up to 10 per cent reduction in particle concentrations through increased vegetation – **but** the results depend on

Figure 3. Increased vegetation can improve air quality

Vegetation should be planted close to the road where the concentrations are highest to catch as many particles as possible.

how vegetation planting is designed, where concentrations can be both positively **and** negatively impacted.

- Vegetation should be planted close to sources of the highest concentrations. For emissions from road traffic, this means low vegetation, close to the road (see Figure 3).
- Use large-area vegetation on which particles can get trapped, such as fuzzy and sticky leaves or needles.
- The polluted air needs to pass through vegetation and not be blocked by obstacles, like plank fences.
- The vegetation must not contribute to pollutants being trapped along streets where people are present, for example by high and dense tree crowns (see Figure 4).
- The vegetation must be managed for many years to come. This can be ensured if the municipality owns the vegetation and allocates resources for its management.

Measures to reduce exposure

Despite all the efforts to reduce concentrations of particles in our city air, particle levels are likely to be higher than they should be for many years to come. One way of influencing exposure is to design city spaces to make places with clean air more attractive to visit than places with higher pollution levels.

Bus stops and stations can be designed with a pleasant setting and seating away from traffic and its emissions. Any covering or weather protection at the stops could be designed to prevent pollutants from reaching the waiting area without limiting their dilution. Creating pedestrian and cycle paths where particle concentrations are lower, such as through parks or shielded from road traffic with sufficiently high fences or hedges, can benefit public health.

Many of our cities are traversed by major roads or heavily trafficked motorways. Where it

Figure 4. Vegetation planted too densely may trap pollutants

Trafficked streets with tall tree crowns can trap the air, increasing exposure by residents compared with a street with free air flow.

Illustration: Petra Wikström

Photo: Adobe Stock

is not possible to redirect roads outside the city centre, one alternative may be to redirect the traffic underground. Attractive urban environments can be created on the surface, offering more space for walking, cycling and greenery. However, it is important to bear in mind that emissions from traffic do not disappear. Instead, they are concentrated at tunnel openings where concentrations can be very high. Measures are required for such exposed locations, such as purifying the ventilated air or preventing access to these areas.

We need measures that solve multiple problems simultaneously

Society strives to reduce exposure to particles through good urban planning. A well-thought-out planning structure, proximity to important locations and measures such as locating pedestrian and cycle paths to areas with low particle concentrations can contribute to better public health.

Meanwhile, we want to reduce particulate matter concentrations by improving transport efficiency and reducing vehicle traffic, but unfortunately there are no signs of any reduction in urban traffic. One problem may be that society

often focuses on solving one problem at a time or that different objectives are not described clearly enough. For example, the transition to fossil-free fuels will lead to a reduction in fossil carbon dioxide emissions, but it will have no effect on air pollution, noise or congestion. Electric vehicles are positive for exhaust emissions and noise, but problems with wear particles and congestion persist. Actually reducing both goods transport and car traffic, for example, through improvements to other modes of transport or transport efficiency, would solve several of the above problems and lead to more lasting improvements in air quality in urban environments.

Further reading

Planning for increased and safer bicycling (boverket.se)

Cykelstaden - En idéskrift om stadsplanering för mainstreamcyklistens återkomst. White, Spacescape, ARQ, Vinnova (spacescape.se)

Lina Sandberg. Vad gör en stad cykelvänlig? En jämförande fallstudie av Helsingborg, Lund och Malmö (diva-portal.org)

Swedish Bicycle Cities (svenskacykelstader.se)

Janhäll, S. (2015) Review on urban vegetation and particle air pollution. Deposition and dispersion. (sciencedirect.com)

Paldanius, A. et al (2019). Grönska i relation till hälsa (amm.se)

Luftkvalitet i stadsutvecklingsprocessen. IVL C470 (diva-portal.org)

Luftkvalitet i stadsutvecklingsprocessen, del 2. IVL C464 (diva-portal.org)

Hållbar stadsutveckling - god luftkvalitet i framtidens täta och gröna städer? IVL C304 (ivl.se)

Ecosystem services - a toolbox 1.0 (cocity.se)

Cleaning the air - PBL knowledge bank (boverket.se)

Healthy city environments with clean air (boverket.se)

Abrahamsson, S. (2016). Vegetationens påverkan på luftföroreningshalter i urban miljö (gu.se)

God luft- och ljudmiljö i stadsplaneringen – En studie i byggnadstypologi och grönska för god luft- och ljudmiljö (chalmers.se)

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Other themed reports from the environmental monitoring programme

Results from the Swedish environmental monitoring programme allow us to describe the current state, reveal changes and assess threats to the environment. The findings from these systematic studies are also used as supporting data for adopting measures. Environmental monitoring themed reports present a selection of findings in a comprehensive manner and in a relevant context.

Luft & miljö 2023
This report takes us on a journey among small, invisible particles that have huge socio-economic costs, mainly through the adverse health effects that they cause. The report is in Swedish.

Luft & miljö 2017
This report focuses on the health of children and the impact of the air quality around them, short- and long-term health effects and the potential for improving air quality to ensure good health. The report is in Swedish.

Air & Environment 2015, Luft & miljö 2015
This report tracks air pollutants to the Arctic and identifies their impact on Arctic air quality and climate and, ultimately, their global impact. The report is available in Swedish and English.

Gifter & miljö
This report presents results from the national monitoring of environmental toxins. It looks at the impact of environmentally hazardous substances in Sweden. The 2020 report examines new challenges and old sins. The report is in Swedish.

Skog & mark
This report presents the results of environmental monitoring of Swedish land environments. The 2020 report looks at ecosystem services, examples and current environmental monitoring related to these services. The report is in Swedish.

naturvardsverket.se/publikationer

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Environmental monitoring for the environmental quality objectives

Environmental monitoring reveals the state of the environment and the results are used to assess whether we achieve Sweden's environmental quality objectives. The 16 objectives have been adopted by the Swedish parliament (the Riksdag) and describe desired conditions in the environment.

naturvardsverket.se/miljoovervakning
sverigesmiljomal.se

Air & Environment

Air & Environment 2023 – Particles takes us on a journey among particles so small that they are invisible but that have huge socio-economic costs every year, primarily through the adverse health effects that they cause.

Are particle concentrations moving in the right direction and are we implementing the necessary measures? Are there factors that risk counteracting positive trends?

Taking the right measures requires a better understanding of particles, identifying their sources and knowing their effects. Research and political leaders bear the responsibility of working together so that we can achieve a society with as low particle concentrations as possible. Tools are available to make progress and it is important that we use them.

The results from Swedish environmental monitoring allow us to describe the current state, reveal changes and assess threats to the environment. They provide important data for international reporting and for evaluating progress towards the environmental quality objective. The findings from these systematic studies are also used as supporting data for identifying and adopting effective measures.

Particles, together with several other air pollutants, are monitored in regional and urban background within the framework of the Swedish EPA's national environmental monitoring programme for air. Swedish municipalities are responsible for assessing whether the environmental quality standards for air, including particles, are met.

NATUR VÅRDS VERKET

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