Achievements and experiences from science – policy interaction in the field of air pollution

Synthesising 20 years of research and outreach, thinking about future needs

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Editors: Stefan Åström, Peringe Grennfelt
For 20 years, the Swedish Environmental Protection Agency together with the MISTRA research foundation have funded air pollution research with focus on producing knowledge that supports policy and emission control in national and international arenas. The research has been multidisciplinary and has included research on emissions, atmospheric transport and transformation processes, human health effects, ecosystem effects and emission control strategies. Research has also been conducted on the interaction between air pollution and climate change. Over these years, the link between the research programmes and the development of emission control strategies and policies in Sweden, the EU, and the UNECE Air Convention has been of high importance. In May 2020, the Swedish Environmental Protection Agency enquired the participants of the latest research programme to summarize these 20 years of research experience in an informative way. The present report constitutes the response to this request.

- The overall aim of the report is to present in how the research programmes have created societal benefits through support for the development of air pollution policies and emission control measures. The report also identifies future research needs to ensure continued progress towards even better air quality for future generations. The report considers four questions originally asked by the Swedish Environmental Protection Agency:

  - How have the research, financed mainly by the Swedish Environment Protection Agency, contributed to increased knowledge and competence within the air pollution context for authorities and the public?
  - How has the research contributed to the Agency’s possibilities to develop Sweden’s air pollution policies nationally and internationally?
  - (How) has the Swedish research contributed to the development of the overall international scientific research within the area?
  - Which are the future challenges and how should the Agency prioritize its research agenda in order to successfully influence national and international air pollution control?

Apart from the support enabled by the active engagement of the civil servants at the Swedish Environmental Protection Agency and MISTRA, the research conducted during these 20 years would not have been possible without all the researchers, research assistants, PhD-students, student supervisors, communicators, project administrators, participants in reference groups and programme boards that have spent years and years dedicated to the research and its outreach. Although too many for us to list them all without risk of forgetting somebody, we extend our thanks to them all for their contributions. With respect to this report we particularly would like to extend our thanks to Per Boberg, Anna Engleryd, Filip Norlén, Maximilian Posch, Enrico Pisoni, Stefan Reis, and Maria Ullerstam for kindly reviewing our draft manuscript. All the errors and mistakes in this final version are our own.
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<th>Abbreviation</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>AMAP</td>
<td>Arctic Monitoring and Assessment Program</td>
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<tr>
<td>AOT40</td>
<td>Accumulated amount of ozone exposure over 40 parts per billion</td>
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<td>AP</td>
<td>Air pollution</td>
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<td>AQ</td>
<td>Air Quality</td>
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<td>ARP</td>
<td>Alpha RiskPoll</td>
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<tr>
<td>ASTA</td>
<td>Swedish research programme “International and National Abatement Strategies for Transboundary Air Pollution”</td>
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<tr>
<td>B/C ratio</td>
<td>Benefit-cost ratio</td>
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<tr>
<td>BC</td>
<td>Black Carbon (sometimes referred to as soot, or elemental carbon), a sub-element of PM(_{2.5}). In this report the easier term ‘soot’ is used.</td>
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<tr>
<td>BC/Al</td>
<td>The ratio between concentrations of base cations and dissolved aluminium</td>
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<td>CAFE</td>
<td>Clean Air for Europe (EU programme)</td>
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<tr>
<td>CAMS</td>
<td>The Copernicus Atmospheric Monitoring Service (CAMS)</td>
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<td>CAPP</td>
<td>The EC proposal for a Clean Air Policy Package</td>
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<td>CBA</td>
<td>Cost-Benefit Analysis</td>
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<td>CC</td>
<td>Climate Change</td>
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<td>CCAC</td>
<td>Climate and Clean Air Coalition</td>
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<td>CCC</td>
<td>Chemical Coordinating Centre under the Air Convention</td>
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<td>CEA</td>
<td>Cost Effectiveness Analysis</td>
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<tr>
<td>CH(_4)</td>
<td>Methane</td>
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<tr>
<td>CLE</td>
<td>Current Legislation</td>
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<tr>
<td>CLEO</td>
<td>Swedish research programme “Climate Change and Environmental Objectives”</td>
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<tr>
<td>CLRTAP</td>
<td>The United Nations Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution (Air Convention)</td>
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<tr>
<td>CO(_2)</td>
<td>Carbon dioxide</td>
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<tr>
<td>COP</td>
<td>Conference of Parties (within the UNFCCC and Minamata Convention)</td>
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<td>COPD</td>
<td>Chronic obstructive pulmonary disease</td>
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<td>CTM</td>
<td>(Atmospheric) Chemistry Transport Model</td>
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<tr>
<td>CVD</td>
<td>Cardiovascular disease</td>
</tr>
<tr>
<td>DG-CLIMA</td>
<td>European Commissions Directorate-General for climate</td>
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<tr>
<td>DG-ENV</td>
<td>European Commissions Directorate-General for environment</td>
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<tr>
<td>EC</td>
<td>The European Commission</td>
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<tr>
<td>EECCA</td>
<td>Eastern Europe, Caucasus and Central Asia</td>
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<td>EMRC</td>
<td>Ecometrics Research and Consulting</td>
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<td>ESM</td>
<td>Earth System Model</td>
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<td>EU</td>
<td>The European Union</td>
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<td>ED Trends</td>
<td>EuroDelta Trends project</td>
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<td>FENO</td>
<td>Fraction of exhaled NO</td>
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<td>GAINS</td>
<td>Greenhouse Gas - Air Pollution Interactions and Synergies (model)</td>
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<td>GHG</td>
<td>Greenhouse gases</td>
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<td>GP</td>
<td>Gothenburg Protocol to the Air Convention</td>
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<td>GTP</td>
<td>Global Temperature Potential</td>
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<td>GWP</td>
<td>Global Warming Potential</td>
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<tr>
<td>GWP(_{20})</td>
<td>GWP over a 20-year time horizon</td>
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<td>GWP(_{100})</td>
<td>GWP over a 100-year time horizon</td>
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<tr>
<td>IAM</td>
<td>Integrated Assessment Model. Air pollution IAMs differ in setup from the climate IAMs</td>
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<td>ICD</td>
<td>Ischemic heart disease</td>
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<tr>
<td>Abbreviation</td>
<td>Explanation</td>
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<tr>
<td>ICP</td>
<td>International Cooperative Programme</td>
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<td>ICP M&amp;M</td>
<td>International Cooperative Programme on the Modelling and Mapping of Critical Levels and Loads and Air Pollution Effects, Risks and Trends</td>
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<tr>
<td>IIASA</td>
<td>International Institute for Applied Systems Analysis</td>
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<tr>
<td>IL</td>
<td>Interleukin (marker of inflammation in the human body)</td>
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<td>ILC</td>
<td>International Law Commission</td>
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<td>IMO</td>
<td>International Maritime Organisation</td>
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<td>LNG</td>
<td>Liquid natural gas</td>
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<td>LUR</td>
<td>Land Use Regression (model)</td>
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<tr>
<td>MATCH</td>
<td>Multi-scale Atmospheric Transport and Chemistry (model)</td>
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<tr>
<td>MC</td>
<td>Marginal cost of emission control</td>
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<tr>
<td>MI</td>
<td>Myocardial infarctions</td>
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<td>MFR</td>
<td>Maximum Feasible Reduction / Maximum Technical Feasible Reduction</td>
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<tr>
<td>MTFR</td>
<td>Maximum Technical Feasible Reduction / Maximum Feasible Reduction</td>
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<tr>
<td>N</td>
<td>Nitrogen</td>
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<tr>
<td>NCM</td>
<td>Nordic Council of Ministers</td>
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<td>NEC</td>
<td>National Emission Reduction Ceilings</td>
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<td>NECA</td>
<td>Nitrogen Emission Control Area</td>
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<td>NEQO</td>
<td>National Environmental Quality Objectives</td>
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<tr>
<td>NH₃</td>
<td>Ammonia</td>
</tr>
<tr>
<td>NMVOC</td>
<td>Non-methane volatile organic compounds</td>
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<td>NOₓ / NO₅</td>
<td>Nitrogen dioxide / Nitrogen oxides (NO and NO₂)</td>
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<td>NorESM</td>
<td>Norwegian Earth System Model</td>
</tr>
<tr>
<td>NPV</td>
<td>Net present value</td>
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<tr>
<td>OC</td>
<td>Organic carbon (sometimes representing condensable)</td>
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<tr>
<td>PM₂.₅</td>
<td>Fine particulate matter with an aero-dynamic diameter smaller than 2.5 µm</td>
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<td>POD</td>
<td>Phytotoxic ozone dose</td>
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<tr>
<td>POLIMP</td>
<td>POLARCAT Model Intercomparison Project</td>
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<tr>
<td>RAINS</td>
<td>Regional Air Pollution Information and Simulation (model)</td>
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<td>RCA4</td>
<td>Rossby Centre regional Atmospheric climate model</td>
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<tr>
<td>RF</td>
<td>Radiative forcing</td>
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<td>RWC</td>
<td>Residential Wood Combustion</td>
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<td>SALSA</td>
<td>Sectional Aerosol module for Large Scale Applications</td>
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<tr>
<td>SCAC</td>
<td>Swedish Clean Air &amp; Climate Research programme</td>
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<td>SCARP</td>
<td>The Swedish Clean Air Research Programme</td>
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<tr>
<td>SCR</td>
<td>Selective catalytic reduction</td>
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<td>SDG</td>
<td>Sustainable development goal</td>
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<tr>
<td>SLCF</td>
<td>Short-Lived Climate Forcers</td>
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<tr>
<td>SNAP</td>
<td>Swedish National Air Pollution and Health Effects Program</td>
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<tr>
<td>SO₂ / SO₅</td>
<td>Sulphur dioxide, Sulphur oxides</td>
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<tr>
<td>Swedish EPA</td>
<td>Swedish Environmental Protection Agency</td>
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<tr>
<td>TFHTAP</td>
<td>Task Force for Hemispheric Transport of Air Pollution</td>
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<tr>
<td>TFIAM</td>
<td>Task Force on Integrated Assessment Modelling</td>
</tr>
<tr>
<td>TFMM</td>
<td>Task Force on Measurement and Modelling</td>
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<tr>
<td>TSAP</td>
<td>Thematic Strategy on Air Pollution</td>
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<tr>
<td>UNECE</td>
<td>United Nations Economic Commission for Europe</td>
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<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
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<tr>
<td>WHO</td>
<td>World Health Organization</td>
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<tr>
<td>WMO</td>
<td>World Meteorological Organization</td>
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ENGLISH SUMMARY

Since the end of the last century, Swedish authorities, primarily the Swedish Environmental Protection Agency and the MISTRA research foundation, have supported five research programmes aiming to increase the scientific understanding of air pollution and to support corresponding national and international policies. The five programmes were the Swedish National Air Pollution and Health programme (SNAP), the International and National Abatement Strategies for Transboundary Air Pollution programme (ASTA), the Swedish Clean Air Research Programme (SCARP), the Climate Change and Environmental Objectives programme (CLEO), and the Swedish Clean Air and Climate Research programme (SCAC).

Sweden and Europe have undergone significant changes in emissions of atmospheric pollutants and their effects over the last 20 years. In parallel the scope of interest has changed from mainly being directed to ecosystems effects within Europe to include health effects and lately also air pollution and climate interactions, both locally and globally.

In this report the five research programmes, outreach activities, and future research needs are presented.

Key scientific achievements

Through continuous funding of research and science-policy interactions by authorities, the Swedish air quality research programmes have since the year 2000 contributed in many ways to expand the knowledge about air pollution. The Swedish research have benefitted from results by foreign research groups (and vice versa), and the Swedish results are not necessarily unique. Nevertheless, there are several important achievements made thanks to these Swedish air quality research programmes throughout the last 20 years. A common theme for all achievements is that they have provided basis for even better estimates of policy instruments’ effectiveness on improving human health and the environment.

Swedish research has shown that European measures to reduce NOx emissions have resulted in decreasing nitrogen deposition since the peak in the 1980s. The measures have also resulted in reductions of the highest percentiles of ground-level ozone in northern Europe. However, the research has shown that nitrogen deposition is still above pre-industrial levels in large parts of Europe. Research has also shown that the impacts of emission reductions of ozone precursors will be more important for future ozone concentrations than the impacts of climate change on the ozone formation, i.e. the climate penalty. But there is an indication that the ozone climate penalty is underestimated during extreme heat waves.

The research programmes have improved knowledge on the exposure of air pollution to humans and ecosystems, and the relative contribution from various sources and compounds. The research has improved modelling tools with respect to a more complete description of exposure to air pollution. The improvements include higher spatial and temporal resolution in emission inventories and exposure assessments, better descriptions of contributions from individual compounds and source categories, as well as improved description of atmospheric physical and chemical processes. Aerosol dynamics and emissions of biogenic terpenes as well as formation of secondary organic aerosols have been included in a
Chemical Transport Model (CTM). A measurement-model fusion approach was utilised for analysis of deposition and ground-level ozone concentration, as well as for production of time-consistent long-term trend analyses. Thereby improving the understanding of atmospheric processes and reliability of impact assessments.

Investigations have shown that air pollution affects our health in many more ways than previously known. Largely thanks to the improved exposure estimates and emission inventories presented above, epidemiological studies in Sweden have revealed associations between long-term exposure to air pollution and mortality, respiratory and cardiovascular diseases, detrimental birth outcomes, dementia, and childhood allergies. Also associations between short-term exposure and mortality, respiratory and cardiovascular diseases, and biomarkers of these diseases have been identified. In addition, Swedish research has shown that the health impact in Sweden is substantial with thousands of excess deaths each year, and that local emissions are important.

The research has improved our understanding of how air pollution harms our health. Experimental chamber studies have shown that exposure to diesel exhaust particles have rapid effects on the pulmonary immune system and on the cardiovascular system, including an impaired ability to dissolve blood clots, vascular dysfunction, and ischemia in the heart muscle in susceptible individuals. These effects are mainly driven by exposure to particles rather than the gaseous components of traffic exhaust, and standard medication did not protect against these effects. Exposure to wood smoke also induces pulmonary and systemic inflammation and detrimental effects on the cardiovascular system. The toxicity of wood smoke depends much on combustion conditions.

Our understanding of, and ability to monitor, how nutrients affect the Nordic ecosystems has increased. Nitrogen can act both as an essential and growth promoting nutrient, and as an air pollutant. Stimulating growth might be beneficial in ecosystems where the goal is to increase primary production. But it is detrimental in ecosystems with naturally limited nutrient availability, where enhanced growth leads to undesirable shifts in species composition and generally to eutrophication. Data from monitoring stations are fundamental for our understanding of the state of the environment and are not fully replaceable by models or calculations. Research that focuses on understanding nutrient cycling can rely on such monitoring data, as these to a large extent are available through publications and open databases. Further, the data are widely used in other nitrogen research and provide important input for summaries and analyses for policy decisions. The last two decades of Swedish nitrogen research featured two key factors which have made the monitoring data particularly valuable and useful. First, it frequently had the width necessary for nitrogen to be assessed in a context of other nutrients and of other environmental factors such as climate change. Second, the monitoring was coordinated and frequently clustered so that the invested resources resulted in data and knowledge suitable for multiple scientific and political purposes. Today, nitrogen monitoring data for the Nordic ecosystems is of use for, e.g., climate change assessments, analysis made in the forestry sector, as well as for fresh- and coastal water management.

Swedish research has improved our understanding of how nitrogen deposition harms our environment. Compared to other European regions, Sweden does not receive more than
moderate nitrogen deposition, except in geographically limited areas in the south-western part of the country. For most of the country area, the maximum nitrogen deposition is modest.

Swedish research has, however, demonstrated that ecosystems that have not been historically exposed to high nitrogen deposition can be negatively impacted even at relatively low nitrogen doses. Furthermore, semi-natural and natural ecosystems react to changes in deposition, but the change involves time lags which could be decade-long. These lags make the causal link between air pollution and ecosystem damage difficult to demonstrate. The degree of resilience to high deposition over an extensive period does not, however, mean that there is no damage. Swedish research has contributed to quantification of the lags between changed deposition and measurable ecosystem effects, and to understanding of how these lags need to be handled by policymakers.

Swedish research has been a main driver behind the development of a new ozone exposure index for vegetation based on leaf ozone uptake, the Phytotoxic Ozone Dose (POD). The POD index quantitatively considers how different European climate conditions affect leaf ozone uptake. As a result, new assessments more accurately show increased relative risks for vegetation damage in northern Europe, compared to other parts of Europe, due to the humid conditions promoting ozone uptake. Furthermore, research has demonstrated long-term changes in the ozone concentrations in northern Europe. The highest ozone concentrations are decreasing, while the lowest concentrations are increasing. Hence, ecosystems and humans have become subject to “chronic” exposure of medium-range ozone concentrations rather than ozone peaks. Moreover, the research has highlighted the potential for an enhanced “climate penalty” in years with heat waves, i.e. that reduced ozone uptake by vegetation during years with summer drought may result in significantly higher ground-level ozone concentrations.

The programmes have improved our understanding of how air pollution and climate change interact. The research has focused on the interactions between air pollution and climate and has led to the development and application of numerical models (e.g. the NorESM and the MATCH models). Within larger international collaborative expert groups (e.g. AMAP), these models have been used to highlight potential co-benefits of reducing emissions of the air pollutants functioning as warming short-lived climate forcers (SLCF) – such as soot1, methane, and ozone – and at the same time improving air quality by decreasing SO2 emissions. Through several scenario studies the programmes showed the importance of integrating air quality effects of climate policies, and vice versa. Finally, of relevance for abatement cost studies, the research has clarified that the ranking of SLCF abatement measures with respect to cost effectiveness is largely independent of the climate metric (such as GWP or GTP) used to estimate the climate change effect of the SLCFs and the measures.

The programmes have highlighted the importance of air pollution emissions in the northern hemisphere for the rapid climate change in the Arctic. Using NorESM, it has been shown that reduced emissions of sulphur at mid-latitudes leads to a local warming but also to increased heat transport towards the Arctic and a warming of the Arctic region. The emission reductions of sulphur between 1990 and 2010 have caused a warming of the Arctic comparable

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1 In this report, the term soot is used instead of black carbon or elemental carbon. The exception is when referred reports or articles use the term black carbon in the title.
to the warming by increased CO2-concentrations. In the future, reductions in sulphur emissions should be compensated by reductions in emissions of warming SLCFs such as soot and methane. There is potential for compensation as a reduction of soot emissions will result in cooling with a 3-5 times larger temperature response per unit reduction in mass compared to warming induced by a corresponding reduction in sulphur emissions.

The programmes have shown how policies have affected past emission trends and how future emissions and environmental effects can develop in response to policies. To ensure cost-effectiveness of policies it is necessary to appropriately separate outcomes of policies on emissions from other drivers. Swedish research was among the first to use data from official emission inventories to quantify outcomes of past policy efforts to reduce SO2-emissions. Effects which are also consistent with publicly reported emission data. In addition, several studies have helped clarify the risk that biofuel policies to combat climate change can increase emissions of air pollutants if additional measures aren’t implemented.

Swedish research has enabled detailed understanding of costs and effects of reducing emissions further. With the importance of using integrated assessment models as a tool for cost-effective air pollution policies, it is central to update these models with best available data on the options available to reduce emissions. Swedish studies within the research programmes have helped improve knowledge on several options not traditionally considered in air pollution policy. Energy efficiency improvements in dwellings and other buildings, emission control technologies on ships, as well as behavioural changes are all measures for which knowledge about effect and costs has been improved by Swedish research.

Swedish research has helped highlighting the importance of focusing air quality policies on air pollution from international shipping. After decades of successful efforts to reduce air pollution from land-based sources, the relative importance of emissions from international shipping has become higher. For the North Sea and the Baltic Sea, Swedish research has helped improve our understanding of the size of the problem, as well as identifying effects and costs of the technologies available to reduce the problem.

The programmes have been important for model validations through international model intercomparisons. Validation of models against observations as well as results from other models is a crucial process to establish that models are realistic. Participation by Swedish researchers in the AMAP and POLMIP model intercomparison efforts has allowed for international networking and coordinated tests of multiple models including operational European and Swedish dispersion models. These intercomparisons have resulted in improved knowledge on atmospheric processes and historical air quality trends.

The programmes have established and improved Swedish competence in air pollution policy integrated assessment modelling. A solid understanding of IAMs helps policymakers understand the usefulness and limitations of the modeling output, which in turn aids policy decisions. In addition, national modelling competence enables transparency and supports the further development of IAMs. The Swedish IAM development has focused on adding climate effects of air pollutants and options for controls of emissions from international shipping to the cost optimization parts of the model.
Key science–policy achievements

In addition to the scientific achievements, the Swedish research programmes have been involved in and promoted mutual interactions between scientists and policymakers both nationally and internationally. More specifically,

The programmes have contributed to the open culture that characterises the air pollution activities in international organisations, in particular the Air Convention. The outcome has become a well-developed trust between scientists and policymakers at different levels. The Air Convention has benefitted from these mutual interactions as a basis for its strategies (e.g. the Saltsjöbaden workshops, the UNECE assessment report Towards Cleaner Air) and the updated Gothenburg Protocol.

The six “Saltsjöbaden” workshops, originally initiated under the ASTA programme, have formed an informal arena for discussions between scientists and different stakeholders on the policy side. International scientists and policymakers have met and discussed key issues of common concern, and the outcome of these workshops has significantly influenced the international air pollution agenda. As examples, the Task Force on Hemispheric Transport of Air Pollutants and the Task Force on Reactive Nitrogen were both established as bodies under the Air Convention after recommendations formulated at Saltsjöbaden workshops. In addition, the programmes have hosted several international expert meetings and workshops, in particular during the ASTA programme. These have mostly been organised in collaboration with the Air Convention, the Nordic Council of Ministers, and the European Union (EU).

The programmes have established sufficient competence of programme scientists to participate as experts in air pollution policy modelling capacity-building exercises in several Eastern European countries. Such capacity building reduces the information and knowledge gap between Western European countries and Eastern European countries during the Air Convention negotiations and thereby mitigates at least one obstacle towards cleaner air.

The close and direct contacts between the research programmes and the Swedish Environmental Protection Agency have been valuable both for the development of national air quality strategies and for the direction of research activities. Programme scientists have been involved as national experts both formally and informally. The availability of an acknowledged roster of experts easily available via phone or email has facilitated Sweden’s work with national and international strategies for cleaner air.

National seminars and conferences have contributed to strengthening the competence and awareness of available actions at various administration levels. Several national outreach activities were held under or in collaboration with the research programmes. At these, results from the programmes have been presented together with state-of-the-art international scientific outlooks. The audience has included, inter alia, representatives from national agencies, local and regional administrations, industry, and Non-Governmental Organisations.

The research programmes have created a cadre of researchers active as experts for national and international air pollution policy activities. These experts have subsequently aided in the development of national air pollution policies, strategies and regulations. They have also served as representatives in international expert bodies. In several of the scientific bodies under the
Air Convention, scientists from the research programmes have played significant roles. These bodies include the TFI AM, TFMM, JEG on Dynamic Modelling, ICP Vegetation, TFRN, WGE and TFHTAP. Other international organisations to which these experts have provided input include the Nordic Council of Ministers, The Arctic Council and its expert bodies, the Climate and Clean Air Coalition, the EU, UNEP, WMO, and the International Law Commission. As a recent example, Swedish experts provided substantial input to the 2015 and 2021 AMAP assessments of the impacts of short-lived climate forcers on the Arctic climate, air quality and human health.

The programmes have improved the air pollution competence within national authorities, companies, and in the public. As examples, several scientists who in the past participated in the programmes are today employed as air pollution experts at national authorities. The programmes have also created several books, multiple reports, and other material aimed at the interested public and students. In addition, experts from the Swedish EPA and other agencies have often participated in programme annual meetings and final conferences. Their participation has simplified knowledge transfer between science and policy.

Additional outcomes from the programmes

The research programmes have enabled Swedish scientists to collaborate with other international research projects and programmes, in particular programmes funded by EU. The research activities presented in this report are not standing alone. Scientists participating in the research presented in this report are also in many cases involved in other research programmes and projects. The research programmes have facilitated for scientists to participate in EU research with a triple benefit for Swedish society: strengthening national research in an international context, direct access for national administrations to frontline results, and formation of common understanding among EU countries.

The research programmes have promoted interdisciplinary studies. The overall thematic approach has requested collaboration across institutional and disciplinary borders. For example, health effects studies have included medicine, atmospheric sciences, and economics.

The long-term financial support and programme format have fostered a cadre of PhD scientists. With short term scientific projects as a basis, there had been much fewer.

The long-term financial support has also made it possible to concentrate activities on key research issues instead of repeatedly write new applications and respond to a lot of administrative requests. Instead, it has resulted in substantial build-up of competence and tools, not the least models, in earlier programmes, with fruitful results emerging within the later programmes.
Sedan slutet av förra seklet har svenska myndigheter, främst Naturvårdsverket och forskningsstiftelsen MISTRA, stöttat fem forskningsprogram med syfte att öka den vetenskapliga kunskapen om luftföroreningar och att stödja nationell- och internationell luftföroreningspolicy. De fem programmen var ”Swedish National Air Pollution and Health programme (SNAP)”, ”International and National Abatement Strategies for Transboundary Air Pollution programme (ASTA)”, ”Swedish Clean Air Research Programme (SCARP)”, ”Climate Change and Environmental Objectives programme (CLEO)”, och ”Swedish Clean Air and Climate Research programme (SCAC)”. 

Svenska och europeiska luftföroreningsutsläpp och dess effekter har förändrats kraftigt de senaste 20 åren. Parallellt har fokus för problemen förändrats från att huvudsakligen vara riktat mot ekosystemeffekter i Europa, till att inkludera hälsoeffekter och nyligen också samverkan mellan luft och klimat, både lokalt och globalt.

I denna rapport presenteras de fem forskningsprogrammen, kommunikations- och samverkansaktiviteter, samt framtida forskningsbehov.

De viktigaste vetenskapliga insatserna
Genom myndigheters kontinuerliga finansiering av forskning och insatser för samverkan mellan forskning och policy har de svenska luftkvalitetsforskningsprogrammen sedan år 2000 på många sätt bidragit till att utöka kunskapen om luftföroreningar. Den svenska forskningen har dragit nytta av resultat från utländska forskargrupper (och vice versa), och de svenska resultaten är inte nödvändigtvis unika. Men det finns flera viktiga insatser som gjorts under de senaste 20 åren tack vare dessa svenska forskningsprogram om luftföroreningar. Ett gemensamt tema för insatserna är att de lagt grunden för ännu bättre uppskattningar av politiska styrmedels effektivitet vad gäller förbättrande av människors hälsa och miljön.

Svensk forskning har visat att europeiska åtgärder för att minska NOₓ-utsläppen lett till minskad kvävedeposition sedan de högsta nivåerna på 1980-talet. Åtgärderna har också resulterat i minskningar av de högsta percentilerna av marknära ozon i norra Europa. Forskningen har dock visat att kvävedeposition fortfarande ligger över förindustriella nivåer i stora delar av Europa. Forskning har också visat att effekterna av utsläppsminskningar av ozonbildande ämnen kommer att vara viktigare för framtida ozonkonzentrationer än klimatförändringarnas effekter på ozonbildningen: klimatpåslaget. Men det finns en indikation på att ozonbildningens klimatpåslag underskattas när det är extrema värmeböjor.

Forskningsprogrammen har förbättrat kunskapen om människors och ekosystems exponering av luftföroreningar samt det relativt bidraget från olika källor och föreningar.

Forskningsprogrammen har förbättrat modelleringssverktoty med avseende på en mer fullständig beskrivning av exponering för luftföroreningar. Förbättringarna inkluderar högre rumslig och tidsmässig upplösning i utsläppsinventeringar och exponeringsbedömningar, bättre beskrivning av bidrag från enskilda föreningar och källkategorier, samt förbättrad beskrivning av fysiska och kemiska processer i atmosfären. Aerosoldynamik och utsläpp av sekundär
organisk aerosol och biogena terpener har inkluderats i en kemisk transportmodell (CTM). En metod för sammanflätning av mätningar och modellering användes för analyser av deponering och ozonkoncentration på marknivå, samt för att skapa tidcksensitiva långsiktiga trendanalyser. Därigenom har förståelsen för atmosfäriska processer och tillförlitligheten av konsekvensbedömningar förbättrats.

Undersökningar har visat att luftföroringar påverkar vår hälsa på många fler sätt än tidigare känt. Till stor del tack vare de förbättrade exponeringsuppskattningarna och utsläppsinventeringarna som presenterats ovan har epidemiologiska studier i Sverige avslöjat samband mellan långvarig exponering för luftföroringar och dödighet, andnings- och kardiovaskulära sjukdomar, komplikationer kopplat till födsel, demens och barnallergier. Även samband mellan kortvarig exponering och dödighet, andnings- och hjärt-kärlsjukdomar och biomarkörer för dessa sjukdomar har identifierats. Dessutom har svensk forskning visat att hälsoeffekten i Sverige är betydande med tusentals fall av överdödighet per år, och att lokala utsläpp är viktiga.


Svensk forskning har varit en viktig drivkraft bakom utvecklingen av ett nytt ozonexponeringsindex för vegetation baserat faktiskt upptag av ozon i löven, ”Phytotoxic Ozone Dose” (POD). POD-indexet tar kvantitativt hänsyn till hur olika europeiska klimatförhållanden påverkar ozonupptag i växters löv. Resultatet är att nya bedömningar mer korrekt visar ökade relativa risker för vegetationsskador i norra Europa, jämfört med andra delar av Europa, på grund av de fuktiga förhållanden som främjar ozonupptag. Vidare har forskning visat långvariga förändringar i ozonkonzentrationerna i norra Europa. De högsta ozonkonzentrationerna minskar medan de lägsta koncentrationerna ökar. Därför blir ekosystem och människor numera utsatta för ”kronisk” exponering av medelhöga ozonkonzentrationer snarare än för ozontoppar. Dessutom har forskningen belyst potentialen för ett utökat ”klimatpåslag” under år med värmeböljor, dvs. att minskat ozonupptag av vegetation under år med sommartorkor kan leda till betydligt högre marknära ozonkonzentrationer.


Programmen har betonat vikten av norra halvklotets utsläpp av luftföröreningar för den snabba klimatförändringen i Arktis. Med hjälp av NorESM visades att minskade utsläpp av svavel vid norra halvklotets mellersta breddegrader leder till en lokal uppvärmning men också till ökad värmeförsörjning mot Arktis och en uppvärmning av den arktiska regionen. Utsläppsminskningarna av svavel mellan 1990 och 2010 har orsakat en uppvärmning av Arktis som är jämförbar med uppvärmningen av ökad CO₂-koncentration. I framtiden bör minskningar av svavelutsläppen kompenseras genom minskade utsläpp av uppvärmande SLCF som sot och
metan. Det finns potential för kompensation eftersom en minskning av sotutsläpp resulterar i kylning med 3-5 gånger större temperaturrespons per massenhet jämfört med den uppvärmning orsakad av motsvarande minskning av svavelutsläpp.

**Programmen har visat hur policies har påverkat tidigare utsläppsstrender och hur framtida utsläpp och miljöeffekter kan utvecklas som följd av policies.** För att säkerställa kostnadsseffektiva policies är det nödvändigt att på lämpligt sätt separera resultaten av policies på utsläpp från andra drivkrafter. Svensk forskning var bland de första som använde data från officiella utsläppsinventeringar för att kvantifiera resultaten av tidigare politiska insatser för att minska SO₂-utsläpp, effekter som också överensstämmer med offentligt rapporterade utsläppsdatal. Dessutom har flera studier hjälpit till att klargöra risken för att biobränslen som sätt att bekämpa klimatförändringar kan öka utsläppen av luftföroreningar om ytterligare åtgärder inte genomförs.

**Svensk forskning har möjliggjort en detaljerad förståelse av kostnader och effekter av ytterligare utsläppsminskning.** Eftersom det är viktigt att använda integrerade beslutstödsmodeller som ett verktyg för kostnadsseffektiv luftföroreningspolicy är det centrale att uppdatera dessa modeller med bästa tillgängliga data om tillgängliga alternativ för att minska utsläppen. Svensk forskning inom forskningsprogrammen har hjälpit till att förbättra kunskapen om flera alternativ som inte traditionellt beaktas som en del av luftföroreningspolicy. Ökad energieffektivitet i bostäder och andra byggnader, teknik för utsläppskontroll på fartyg, samt beteendeförändringar, är alla åtgärder för vilka kunskapen kring effekt och kostnad har klargjorts av svensk forskning.

**Svensk forskning har bidragit till att betona vikten av att fokusera luftkvalitetspolicies på luftföroreningar från internationell sjöfart.** Efter årtionden av framgångsrika ansträngningar för att minska luftföroreningar från landbaserade källor har den relativa betydelsen av utsläpp från internationell sjöfart blivit högre. För Nordsjön och Östersjön har svensk forskning inom forskningsprogrammen bidragit till att förbättra vår förståelse av problemets storlek, samt att identifiera effekter och kostnader för de tekniker som finns för att minska problemet.

**Programmen har varit viktiga för modellvalidering genom internationella modelljämförelser.** Validering av modeller gentemot observationer såväl som resultat från andra modeller är en avgörande process för att fastställa att modeller är realistiska. Deltagandet av svenska forskare i AMAP- och POLMIP-modellinsatserna för jämförelse har möjliggjort internationellt nätverkande och samordnade tester av flera modeller inklusive tillämpade europeiska och svenska utsläppsspridningsmodeller. Dessa jämförelser har resulterat i förbättrad kunskap om atmosfäriska processer och historiska luftkvalitetsstrender.

**Programmen har etablerat och förbättrat svensk kompetens inom integrerad beslutstödsmodellering (IAM) för luftföroreningspolicy.** En solid förståelse av IAM hjälper beslutsfattare att lita på modellernas resultat och känna till deras begränsningar, vilket i sin tur underlättar policybeslut. Dessutom möjliggör nationell modelleringssystemets transparens och hjälper till att vidareutveckla IAM-modeller. Den svenska IAM-modellutvecklingen har fokuserat på att lägga till klimateffekter av luftföroreningar samt åtgärder för utsläppsminskning från internationell sjöfart till kostnadsoptimeringsdelarna i modellen.
De viktigaste insatserna i gränslandet mellan vetenskap och policy

Förutom de vetenskapliga insatserna har de svenska forskningsprogrammen varit inblandade i, och främjat, olika former av ömsesidiga interaktioner mellan forskare och beslutsfattare både nationellt och internationellt. Mer specifikt,

Programmen har bidragit till den öppna kultur som kännetecknar luftförorenings-aktiviteter i internationella organisationer, särskilt Luftvårdskonventionen. Resultatet har blivit ett väl utvecklat förtroende mellan forskare och beslutsfattare på olika nivåer.
Luftvårdskonventionen har dragit nytta av dessa ömsesidiga interaktioner som grund för dess långsiktiga strategier (t.ex. Saltsjöbaden-konferenser, UNECEs granskningsrapport 'Towards Cleaner Air'), samt det uppdaterade Göteborgsprotokollet.


Programmen har skapat tillräcklig kompetens hos forskare för dem att delta som experter vid kapacitetsuppsyggande utbildningar i modellering för luftvårdsförflyttning i flera östeuropeiska länder. Sådan kapacitetsuppsyggnad minskar informations- och kunskapsflykt mellan västeuropeiska länder och östeuropeiska länder under Luftvårdskonventionens förhandlingar, och minskar därmed minst ett av hindren mot renare luft.

De nära och direkta kontaktdyna mellan forskningsprogrammen och Naturvårdsverket har varit värdefulla både för utvecklingen av nationella luftvårdsstrategier och för rikten av forskningsaktiviteter. Forskare i programmen har varit inblandade som nationella experter både formellt och informellt. Tillgängligheten av en lista över experter som är lätt tillgänglig via telefon eller e-post har underlättat Sveriges arbete med nationella och internationella strategier för en renare luft.

Nationella seminarier och konferenser har bidragit till att stärka kompetensen och kunskapen om tillgängliga åtgärder på olika förvaltningsnivåer. Flera nationella kommunikationsaktiviteter hölls under eller i samarbete med forskningsprogrammen. Vid dessa har resultat från programmen presenterats tillsammans med nya resultat från den internationella forskningsfronten. Åhörare har bland annat inkluderat företrädare för nationella myndigheter, lokala och regionala förvaltningar, industrirepresentanter, samt icke-statliga intresseorganisationer.

Programmen har förbättrat kompetensen kring luftföroreningar inom nationella myndigheter, företag och i allmänheten. Som exempel är flera forskare som tidigare deltagit i programmen idag anställda som luftföroreningsexperter hos nationella myndigheter. Programmen har också skapat flera böcker, många rapporter och annat material riktat till intresserad allmänhet och studenter. Dessutom har experter från Naturvårdsverket och andra byråer ofta deltagit i programmets årsmöten och slutkonferenser. Deras deltagande har förenklat kunskapsöverföringen mellan vetenskap och beslutsfattare.

Ytterligare resultat från programmen

Forskningsprogrammen har gjort det möjligt för svenska forskare att samarbeta med andra internationella forskningsprojekt och program, särskilt program finansierade av EU. De forskningsaktiviteter som presenteras i denna rapport står inte helt på egen fot. De forskare som deltagit i programmen som presenteras i denna rapport har också i många fall varit involverade i andra forskningsprogram och projekt. Forskningsprogrammen har underlagt för forskare att delta i EU-forskning med en trippel fördel för det svenska samhället: stärka nationell forskning i ett internationellt sammanhang, ge nationella myndigheter direkt tillgång till senaste kunskap om luftkvalitet och luftpolicy, samt bildande av gemensam förståelse för luftkvalitetsfrågor bland EU-länder.

Forskningsprogrammen har främjat tvärvetenskapliga studier. Det övergripande tematiska tillvägagångssättet i forskningsprogrammen har krävt samarbete över institutionella och disciplinära gränser. Studier av hälsoeffekter har till exempel behövt inkludera expertis inom medicin, atmosfärsvetenskap och ekonomi.

Det långsiktiga ekonomiska stödet och programformatet har möjliggjort för ett flertal forskare att genomgå en forskarutbildning. Med kortsiktiga vetenskapliga projekt som grund hade de varit mycket färre.

Det långsiktiga ekonomiska stödet har också gjort det möjligt att koncentrera verksamheten till viktiga forskningsfrågor istället för att upprepa gånger skriva nya ansökningar och svara på många administrativa förfrågningar. Istället har det resulterat i en betydande uppbyggnad av kompetens och verktyg, inte minst modeller, i de tidiga programmen, med fruktabara resultat som framkommit inom de senare programmen.
Almost all economic activities cause air pollution with detrimental effects to ecosystems, human health, and society. Air pollution effects covered in this report are human health risks, acidification, eutrophication, vegetation damages and air pollution-related effects on climate.

The World Health Organization (WHO) has identified that the largest health risk from environmental causes is that of human exposure to PM$_{2.5}$ in ambient air (1, 2). PM$_{2.5}$ in ambient air mainly consists of emitted primary particles, and of secondary particles (such as ammonium nitrates and ammonium sulphates) formed in the atmosphere from emitted gases such as volatile organic compounds (VOC), nitrogen oxides (NO$_x$), sulphur dioxide (SO$_2$), and ammonia (NH$_3$). Human exposure to PM$_{2.5}$ is associated with premature mortality, heart and lung related diseases, and many other illnesses (3). In 2018, some 417,000 premature fatalities per year was estimated to occur in Europe due to PM$_{2.5}$ in ambient air (4). In Sweden the number of fatalities directly linked to PM$_{2.5}$ exposure is estimated at some 4,700 in 2015 (5). The most recent projections indicate that air pollution by 2030 will cause some 168,000 premature fatalities per year in the EU (6).

SO$_2$, NO$_x$ and NH$_3$ emissions are also, when deposited, causing acidification of forest soils and freshwaters. Sweden is one of the European countries that still suffers from acidification damages. Although recovery is ongoing, Swedish estimates show that 17% of the Swedish catchment areas were in 2010 exposed to acid deposition exceeding critical loads for surface water acidification. The number is expected to have decreased to 10% by 2020 (7). Further, reports are now documenting biological recovery in European lakes and streams that were previously uninhabitable for several species due to acidification (8). Nevertheless, several European ecosystems are projected to experience problems with excessive acidification for decades to come (6, 9, 10).

Another threat to ecosystems is eutrophication of soils and waters due to emissions of NH$_3$ and NO$_x$ (11). With respect to eutrophication, current trends and projections show declining but remaining problems in large parts of Europe and these problems are expected to remain due to slow NH$_3$ emission reductions within the agricultural industry.

Damages from tropospheric ozone to human health, crops, and ecosystems due to emissions of the ozone precursors NO$_x$ and non-methane volatile organic compounds (NMVOC) are also a serious problem in Europe (12, 13). The trend for ozone damages is however less clear. Results indicate a mixed picture with decreasing peak ozone level concentrations but increasing annual average concentrations. This mixed picture is due to European emission reductions of ozone precursors (which reduce peak concentrations) and increased inflow of ozone from other continents in combination with increased methane (CH$_4$) emissions (increasing average concentrations).

Air pollution emissions are also influencing climate change through their masking or unmasking of the warming from high carbon dioxide (CO$_2$) emissions. Those air pollutants affecting climate change are called Short-Lived Climate Forcers (SLCF) and may have
significant climate effects over medium-range time scales. The effects of SLCF have been particularly important for the observed temperature increase in the Arctic region. Particles and tropospheric ozone are important SLCFs. Particles may both increase and decrease temperature in the atmosphere. While sulphate and nitrate particles are reflecting sunlight and thus are cooling, black soot particles are warming.

To understand the complex nature of air pollution and all its adverse effects, and to understand how to reduce the problem in socially acceptable as well as cost-effective ways, it is important to invest in research answering to these needs. For about 20 years, starting in 1999, policy-oriented air pollution research in Sweden has been concentrated to five research programmes with the aim to support national and international policies.

Nationally, most of the research has been related to the National Environmental Quality Objectives (NEQO). The research has also been of importance for sector policies such as transportation, energy, and forestry. With respect to international environmental policies, research priorities have mainly been given to the policy development under the United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution (CLRTAP, currently most often called the Air Convention) and the European Union. Additional international policy organizations and processes of relevance are the Arctic Council, Climate and Clean Air Coalition (CCAC) and WHO (AQ guidelines).

The research activities have been focused on six areas:

a) atmospheric transformation, transport, and distribution of pollutants,

b) human health effects,

c) effects on ecosystems (S and N deposition and direct effects from ozone),

d) effects on climate,

e) the interface between science and politics, and

f) concepts and methods for policies including costs and benefits of emission control.

The aim of this report is to document and present the research programmes and associated outreach activities, the background and priorities set, the main scientific and policy outcomes, as well as future research needed to better solve the remaining air pollution challenges. The report is based on our own experiences from working within the five programmes.

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2 https://www.sverigesmiljomal.se/miljomalen/
2. SWEDEN’S AIR POLLUTION AGENDA

The decades before 2000, Sweden’s air pollution agenda was almost entirely directed towards acid rain and related problems. After acid rain became an issue of public and political interest around 1970, and its international dimensions became clear, the key policy was to reduce emissions in Sweden but also to make other countries aware of the problem and form common strategies and agreements to reduce emissions (14). Health effects, although realized as an issue, were not considered with the same approach. Even if other problems, e.g., mercury and persistent organic pollutants, were highlighted, they did not receive the same level of attention. Health effects were included in the agenda, but actions were mainly following international policies developed by the EU and WHO. Strict regulations on passenger cars requiring catalytic converters were not introduced until around 1990.

In this landscape, the millennium formed a shift in air pollution policies both in Sweden and internationally. The signing of the Gothenburg Protocol (GP) under the Air Convention just a month before the millennium was a milestone in the international efforts to reduce air pollution. The protocol committed signatories to reduce their emissions to levels that weren’t thought of a few years earlier. Many felt relief after the hard work getting the agreement through, so plans for the coming period were not well developed. The protocol was a significant step forward, but additional measures were necessary to meet the long-term environmental goals. Health effects, which weren’t a significant part of the negotiations, were also becoming more important. The European Union was, in parallel with the Air Convention, developing its own strategy and decided on similar reductions as the GP through the National Emission Ceilings (NEC) Directive. Both decisions urged for taking the air pollution policies further based on science. For these new steps in the control of air pollution, there was a need to revisit the underlying science regarding transport, chemistry, and effects as well as the methods used for setting priorities, including new knowledge on, e.g., health effects.

Sweden, with its long tradition of being at the forefront in the development of international air pollution strategies and promoting actions, realized that there was a need for keeping the agenda active and taking new actions. This was a main reason for MISTRA announcing a new research programme in 1998.

For Sweden, the probably most important change at this time was the establishment of the National Environmental Quality Objectives (NEQO), which was decided by the Swedish government and parliament in 1999 (15). Prior to the establishment of the NEQO system, the number of environmental goals and commitments were growing and formed a system that was

SUPPORTING PUBLIC KNOWLEDGE
3 books produced:
*Transboundary Air Pollution: Scientific Understanding and Environmental Policy in Europe (2007, ed: Håkan Pleijel)

*Air Pollution and Climate Change: Two Sides of the Same Coin? (2009, ed: Håkan Pleijel)

*Governing the Air: The Dynamics of Science, Policy, and Citizen Interaction (2011, eds: Rolf Lidskog, Göran Sundqvist)
difficult to handle both from a political and an administrative point of view. In the new system, there was first an overarching “Generational objective” and seven policy formulations, which together presented the long-term directions of the Swedish society and environment. Within the overarching objective and policies, 15 (later 16) separate and more specific NEQOs were established. Several of these are connected to air pollution but there are three that are of special importance: Natural Acidification Only, Clean Air, and Zero Eutrophication. In addition, air pollution is strongly linked to climate change, and the objective Reduced Climate Impact should also be considered in the context of air pollution. The achievement of the NEQOs have been evaluated regularly. In the latest assessment, from 2019, it is concluded that none of the objectives related to air pollution is achieved (16).

The research programmes presented in this report have been directed to three areas all associated with the above-mentioned NEQOs:

- Forming a scientific basis for international negotiations, primarily with respect to the Air Convention and the EU.
- Improving the scientific knowledge on the NEQOs, with respect to setting air quality standards, assessing the outcome of actions taken and outlining options for future control (scenarios).
- Assessing various sector approaches.

Since Sweden to a large extent is affected by air pollution from sources in other countries, international activities are of utmost importance for achieving the NEQOs. In fact, none of the air pollution-related NEQOs can be reached without reducing emissions in other countries in Europe. Promoting international agreements within the EU, the Air Convention, and the International Maritime Organization (IMO) are therefore an important part of the activities under the NEQOs. There are several examples of how Sweden, often together with other Nordic countries, have actively worked to promote international agreements taking European emissions to lower levels. The May 2012 Amendment of the GP under the Air Convention was preceded by active footwork by Swedish and other Nordic policymakers, and the 2016 assessment report “Towards Cleaner Air” (17), which formed the basis for the most recent strategy within the Air Convention, would not have been possible to realize without initiatives and funds from Nordic agencies.
3. THE RESEARCH PROGRAMMES

Short historical overview

Structured scientific research on air pollution in Sweden goes back to the 1960s, when the environmental degradation became an issue of national and international concern. At the beginning, the interest was directed to local air quality linked to emissions from industries and urban heating. The focus was on human health, primarily pulmonary disease, and nuisance, e.g. from odorous compounds and soiling through deposited particles (e.g. soot).

At the end of 1960s, after alarming reports of an ongoing acidification of Swedish and Norwegian lakes and streams, to a significant degree caused by transboundary transport of air pollutants, research priorities turned to acid deposition and related problems. During the rest of the 20th century, regional air pollution problems were a top priority for the Swedish research agenda. Most of the research was run as single, un-coordinated, projects financed by the Swedish EPA, although some coordination of research activities occurred during the 1980s, e.g. the acid rain research at the lake Gårdsjön (18, 19). Local air pollution was given less priority, but limited research programmes on this topic were set up by the Swedish EPA during the 1980s.

At the end of 1990s, the Swedish Environmental Protection Agency (Swedish EPA) lost its budget for supporting research, causing large concern among both policymakers and scientists. To keep research activities going, the scientific research foundation MISTRA took over the responsibility of the research on two international environmental problems of high Swedish interest: transboundary air pollution and eutrophication of the Baltic Sea. For air pollution, MISTRA together with other funders supported a large integrated research programme; International and National Abatement Strategies for Transboundary Air Pollution (ASTA). The organisation of the research also changed; the previous support of individual, mostly short-term, projects given to one scientist or one research group was by MISTRA replaced by a structure of large, long-term, and continuous programmes involving several research groups.

The new structure, which has continued throughout the entire period, have had several advantages. It has increased capacity for participating scientists to act as experts via day-to-day communication with agencies and in expert groups as well as knowledge-sharing in international environments. It has also increased the credibility of Swedish scientists and has thereby enabled international acceptance of Swedish researchers as having leading positions in several international expert groups over the years. Further, it has enabled a functional transdisciplinary research community and cross-disciplinary research activities. The consecutive national research programmes have led to long-lasting productive collaborations in the air pollution research community that continues to this day and enabled Swedish participation in larger European research projects. Further still, it has ensured rejuvenation of the roster of scientists working with the NEQOs, through the possibility to finance Master-
students, PhD-students as well as through laying the academic foundation necessary for appointment of Associate professors. As an extra bonus the new structure reduced time needed for administrating research, both for agencies and research institutions (See also section 5 and 6).

### 3.1. ASTA – International and National Abatement Strategies for Transboundary Air Pollution

The main aim of the ASTA programme was to support the development of science-based policies on transboundary air pollution in Europe. Priorities and deliverables were set in the perspective of the agendas under the Air Convention as well as the EU, which during the time of ASTA developed a Thematic Strategy on Air Pollution called Clean Air For Europe (CAFE). The programme followed the principles of MISTRA by having a programme board with representatives from a few key stakeholders. In addition to MISTRA, the programme was supported by the electricity industry organisation ELFORSK, the National Board of Forestry, the Swedish Energy Agency, and the Ministry of Environment. In this way the relevance of the research was continuously evaluated. The programme was divided into two phases and evaluated by an international panel both before the start of the programme and before its second phase. The programme was also evaluated after its finalization.

The ASTA programme carried out research on regional transport and transformations of particulate air pollution, acidification of soils and water, the effects of nitrogen (N) input to forest ecosystems, the effects of ground-level ozone on vegetation, and costs and benefits of air pollution control. Nitrogen issues were a prominent part of the programme, including studies and modelling of the dynamics in biodiversity due to increased N input. As part of the studies on acidification to ecosystems, the acidification effects of increased extraction of forest biomass were also studied. A special project was also directed towards social science, focusing on how bridging concepts are formed and used in the interaction between scientists and policymakers. In addition to the scientific research, the programme had a significant budget for science – policy dialogues and communication of results from the programme.

An important part of the programme was to organize international meetings to present and discuss ways forward. These include the so-called Saltsjöbaden meetings, which are further presented in chapter 4, with the first two mainly organised as ASTA activities. In addition, it is worth mentioning that the ASTA programme took the initiative to form the Joint Expert Group on Dynamic Modelling (JEG), first loosely connected to the Air Convention and since 2020 an official activity under the Air Convention. Further information, e.g. access to annual reports etc., is given at ASTA’s web page http://asta.ivl.se.

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**ASTA**

**Duration:** 1998–2007,  
**Funder:** MISTRA,  
**Budget:** ~65 million SEK,  
**Co-ordinator:** Peringe Grennfelt,

**Main Content:** Atmospheric processes; Ecosystems effects from ozone, Deposition of sulphur and nitrogen; Abatement strategies, Science-policy interactions, Workshops

**Policy achievements:** Support to the EU CAFE strategy, new initiatives within the Air Convention, national forest policies and the NEQOs *Natural Acidification Only, Clean Air* (ground-level ozone), and *Zero Eutrophication.*
3.2. SNAP – Swedish National Air Pollution and Health Research programme

Despite being the original cause of concern for poor human health, health effects attributable to air pollution were given little attention in research before 2000. However, after international epidemiological studies in the 1990s showed that air pollution contributed significantly to premature deaths (20-23), the interest increased. After 2000, health effects have become the main driver for air pollution policies.

After refinancing the Swedish EPA’s research agenda, health effects from air pollution became a priority area and after a research call, the Swedish National Air Pollution and Health Effects Program (SNAP) received support. The programme was led by the Karolinska Institute and directed by a group with representatives from the Swedish EPA, the Swedish Energy Agency, and the vehicle industry organisation “BIL Sweden”.

One aim of SNAP was to better estimate the exposure from especially traffic and domestic wood burning. A method for quantifying the general population exposure to air pollutants in Sweden, the URBAN model, was developed, and was later used for national health impact assessments. Another project focused on the particle concentrations in Stockholm, for the first time using the number of ultrafine particles as measure. SNAP included human exposure studies both with an exposure chamber and in a real road tunnel. The epidemiological projects were mainly focused at short-term and long-term air pollution exposure and myocardial infarction, and on the effect on asthma incidence in children and in adults. A couple of studies included a novel gene-environment component.

3.3. SCARP – The Swedish Clean Air Research Programme

When the ASTA and SNAP programmes ended in 2006, the Swedish EPA opened for a new research programme including both health and environmental effects. A consortium with a background in ASTA and SNAP won the call and received a grant for six years ending in 2012. Priority issues were largely the same as in the earlier programmes, with an additional work package on integrated assessment modelling (IAM) and policy support. Particles, their origin, and role for health effects were given high priority. Characterisation of different PM fractions were made, e.g. with respect to source origin and their content of elementary and organic carbon. Special attention was given to air pollution effects on children. For ecosystems, priorities were given to the effects of nitrogen deposition on biodiversity.
During the SCARP programme, the issue of Short-Lived Climate Forcers (SLCF) emerged and some of the issues were picked up in the programme. Scientists within SCARP contributed to the development of our understanding of the interplay between air pollution and climate change, a challenge that gained international recognition with the publication of the UNEP & WMO report “Integrated Assessment of Black Carbon and Tropospheric Ozone” (24). This report was influential and was part of the reason why the Climate and Clean Air Coalition (CCAC)3 was established.

The programme involved many issues of importance for local air pollution and two national seminars focusing on needs from local administrations were held in Stockholm 2007 and 2013. The first seminar was also a summing up of the ASTA and SNAP programmes.

The SCARP programme had a limited budget compared to the ASTA and SNAP programmes. The Swedish EPA allowed for a large degree of freedom for the consortium to organize the research but nevertheless participated in the programme meetings. Further information is given at the SCARP web page https://www.scarp.se/

### SCARP

**Duration:** 2007-2012,  
**Funder:** Swedish EPA,  
**Budget:** ~36 million SEK,  
**Co-ordinator:** Peringe Grennfelt,  
**Web page:** [http://www.scarp.se](http://www.scarp.se)

**Main Content:** Atmospheric particles and their health effects; particles and climate interactions, ecosystems effects from N deposition, policy support modelling. Saltsjöbaden III and IV.

**Policy achievements:** Support to the NEQOs Natural Acidification Only, Clean Air, and Zero Eutrophication. To some extent also to Reduced Climate Impact.

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3 https://ccacoalition.org/en
3.4. CLEO – Climate Change and Environmental Objectives

Climate change – air pollution interactions were also brought up in a separate programme, Climate change and Environmental Objectives (CLEO), set up in 2010. The overall objective was to investigate how changes in climate, such as temperature, precipitation and run-off, affect our potential to achieve the NEQOs that are influenced by long-range transport of air pollution and to analyse synergies and conflicts between national and international measures that aim to reduce emissions of greenhouse gases and other air pollutants. The programme focused on the NEQOs Clean Air, Natural Acidification Only, Zero Eutrophication and to some extent A Non-Toxic Environment. Issues related to climate change and the marine environment were synthesized based on results from other research programmes.

Using projections for climate change, air pollution emissions and forest management as input, the CLEO scientists analysed future scenarios of surface ozone, particle pollution, leaching of nitrogen, recovery from acidification and leaching of mercury. Further information is given at the CLEO web page [www.cleoresearch.se](http://cleoresearch.se/).

Table: CLEO

<table>
<thead>
<tr>
<th>Duration:</th>
<th>2010-2015,</th>
</tr>
</thead>
<tbody>
<tr>
<td>Funder:</td>
<td>Swedish EPA,</td>
</tr>
<tr>
<td>Budget:</td>
<td>40 million SEK,</td>
</tr>
<tr>
<td>Co-ordinator:</td>
<td>John Munthe,</td>
</tr>
<tr>
<td>Web page:</td>
<td><a href="http://cleoresearch.se/">http://cleoresearch.se/</a></td>
</tr>
</tbody>
</table>

Main Content: CC influence on the possibilities to achieve the NEQOs for other objectives; synergies and conflicts between CC policies and policies for achieving NEQOs.

Policy achievements: Support to policies with respect to the NEQOs Natural Acidification Only, Clean Air (ground-level ozone), Zero Eutrophication, and Reduced Climate Impact.

3.5. SCAC – Swedish Clean Air & Climate Research programme

In the Swedish Clean Air and Climate research programme (SCAC), 2013-2020, the scope was, in similarity to SCARP, widened to include some aspects closely related to climate change. One such aspect was how air pollution emissions are influencing the climate at Northern latitudes. Another link between air pollution and climate change was how ozone exposure might influence the uptake of carbon in forest ecosystems and in this way counteract the role of forests in binding carbon dioxide. The link between air pollution and climate change was also a key research subject in the integrated assessment modelling of emission control strategies made in SCAC.

Health effects from local sources such as road traffic and disperse sources, such as small-scale wood combustion, were key issues of concern in SCAC. Studies were directed to three cities in Sweden. A comprehensive air quality modelling study was carried out which allowed to estimate concentrations and exposures from regional scale down to street level, including
source appointments of the exposure estimates. The exposure effect studies indicated health effects at concentrations well below present air quality guidelines. The need for further emission control was in this way given more arguments.

Special emphasis was placed on developing robust systems and processes for emission forecasts and scenarios, as well as on developing indicators, methods, and models for evaluating and assessing the cost-effectiveness of various action alternatives. Further information is given on the SCAC web page www.scac.se.

### SCAC I and II

**Duration:** 2013-2016 + 2016-2020,  
**Funder:** Swedish EPA,  
**Budget:** 25+12 million SEK,  
**Co-ordinator:** John Munthe & Peringe Grennfelt,  
**Web page:** [http://www.scac.se](http://www.scac.se)

**Main Content:** Human particle exposure and health effects; effects on ecosystems from ozone and N deposition; climate effects from SLCF; synergies and conflicts between actions on air pollution and CC. Saltsjöbaden workshops V and VI.

**Policy achievements:** Support to international air pollution policies, including the Air Convention, Arctic Council and CCAC. Support to the NEQOs **Natural Acidification Only**, Clean Air, **Zero Eutrophication**, and Reduced Climate Impact.

### 3.6. International research programmes and other activities benefiting from the Swedish research and vice versa

The research programmes presented in this report are not standing alone. They are rather parts of larger research efforts forming basic research and infrastructures as well as targeted research and assessment activities on air pollution. These combined efforts are often difficult to disseminate, and the research often form a web of activities involving both national and international collaboration. The collaboration with other scientific communities has also offered unique possibilities for exchange of information and being in the frontline of discussions and presentations of new findings. In fact, the Swedish research programmes have offered unique possibilities for taking part, sometimes taking a lead, in several EU-funded research programmes (Table 3). The already existing Swedish research programmes has also made it possible to include aspects of Swedish (Nordic) interests in EU projects.

In addition, activities such as air pollution monitoring programmes (urban and regional AQ, EMEP and others), emission inventories and assessments obtain data and information of direct use in the programmes. The importance of these possibilities is often underestimated, and unfortunately credit to those responsible for these activities is not always received.

Internationally, EU’s research programmes have formed one of the strongest partners to those programmes presented in this report.

Table 1 exemplifies some of the most important programmes. The importance can be of various kind: policy, scientific or budgetary.
Table 1: International research projects of particular importance for the 20 years of Swedish research

<table>
<thead>
<tr>
<th>Research project incl. acronym</th>
<th>Main financing organisations</th>
<th>Running years</th>
<th>Scientific area</th>
<th>Participation institution*</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCEPTED</td>
<td>ERA-NET</td>
<td>2013-2015</td>
<td>Health, air pollution exposure, climate, future scenarios.</td>
<td>UMU, SMHI</td>
</tr>
<tr>
<td>BioDiv-Support</td>
<td>Belmont Forum/ BiodivERsA</td>
<td>2019-2022</td>
<td>Biodiversity, climate, air pollution, future scenarios</td>
<td>SMHI, GU, LU, SU</td>
</tr>
<tr>
<td>ECLAIRE</td>
<td>EU</td>
<td>2011-2015</td>
<td>Ozone and ecosystems, cost-benefit analysis,</td>
<td>IVL, GU, SMHI</td>
</tr>
<tr>
<td>ESCAPE</td>
<td>EU</td>
<td>2008-2012</td>
<td>Air pollution cohort studies</td>
<td>KI, UMU</td>
</tr>
<tr>
<td>EUA-BCA</td>
<td>EU</td>
<td>2018-2021</td>
<td>Soot, health, climate, Arctic Warming</td>
<td>IVL</td>
</tr>
<tr>
<td>IMPACT2C</td>
<td>EU</td>
<td>2011-2015</td>
<td>Climate, air pollution scenarios</td>
<td>SMHI</td>
</tr>
<tr>
<td>NEPAP</td>
<td>EU</td>
<td>2002-2005</td>
<td>Background atmospheric concentrations, non-linearities, nitrogen deposition, particles, and uncertainties in source-receptor relationships.</td>
<td>IVL, SMHI</td>
</tr>
<tr>
<td>NitroEurope Project (NEU) link</td>
<td>EU</td>
<td>2006-2011</td>
<td>Ecosystems, health, and systems analysis</td>
<td>IVL</td>
</tr>
<tr>
<td>Nordic Welfair link</td>
<td>Nordforsk</td>
<td>2016-2021</td>
<td>Health and systems analysis</td>
<td>SMHI, UMU, IVL</td>
</tr>
</tbody>
</table>

*UMU = Umeå University, SMHI = Swedish Meteorological and Hydrological Institute, GU = Göteborg University, LU = Lund University, SU = Stockholm University, IVL = IVL Swedish Environmental Research Institute, KI = Karolinska Institutet,

Another important type of activity that deserves special mentioning is how these Swedish research programmes have increased the quality in the regular in-depth evaluations of the NEQOs (25), the state of the environment, and in dedicated environmental policy impact assessments.

SUPPORTING FACT-BASED SWEDISH ENVIRONMENTAL POLICY

Participated with national expert input to:

- Governmental official investigations, latest example SOU 2016:83.
- In-depth evaluations of the NEQOs, latest example from the CLEO research programme in 2015
4. THE SALTSJÖBADEN SCIENCE-POLICY WORKSHOPS

The 1999 Gothenburg Protocol was the first protocol to set targets for effects on ecosystems and by integrated assessment modelling translate these into country targets on emissions. Countries' policies and commitments thereby became central for assessing the probability of reaching the ecosystem targets. It was also an example of using the precautionary principle by allowing for a coarse system of the underlying science as good enough decision support, and an example of striving for cost-effective environmental policy by using data on control options and their costs as basis for commitments by the parties to the protocol.

As mentioned above, the millennium formed a shift into a new era in many ways. The last 20 years have been characterised by dynamic shifts in both science and policy, which the Swedish research programmes have been part of. One way to describe these dynamics is to follow the topics and outcomes of the so called Saltsjöbaden workshops as well as some other gatherings between science and policy during this period. These workshops, all together six, have all to a substantial part been organised by scientists from the research programmes presented here. The programmes (particularly ASTA) have also to some extent been financially supporting the workshops. Main support for the workshops after the ASTA programme period has however been directly from the Swedish Environmental Protection Agency and the Nordic Council of Ministers. The following section presents the background and main outcomes of the Saltsjöbaden workshops. Further information, e.g., workshop conclusions and presentations can be found at the Saltsjöbaden VI web page https://saltsjobaden6.ivl.se.

4.1. The post-GP start-off – the first Saltsjöbaden workshop

It all started in 1999, when the ASTA programme was in its initial phase. Within the programme board, there were discussions on how to restart the science and policy work after the signing of the Gothenburg Protocol. The science-policy work had been so focussed on getting the agreements finalised, that next steps had not really been on the agenda. They concluded that it was the right time for organising a workshop under the ASTA umbrella to discuss future challenges and needs for the international air pollution agenda. A programme committee was set up and, thanks to some unspecified programme funding within ASTA, a workshop was organised in the suburban village Saltsjöbaden outside Stockholm in April 2000.

The idea of a workshop was very well received by the international community and the 3-day workshop attracted more than 100 participants. The format was open, and participants felt relieved to discuss environmental concerns in small groups without having to defend national positions in negotiations. The outcome of the workshop was summarized in several recommendations, each equipped with a label suggesting a responsible organization for the recommendation (26).

In planning of the workshop, the ideas were very much focused on a continuation of the work in preparation of the Gothenburg Protocol with refinements of the technical and scientific ideas, although there were thoughts around sector integration, going from cost-effectiveness to cost-

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1 Programme chair Lars Lindau (Sweden) and programme director Peringe Grennfelt (Sweden)
benefit, and widening of scales. The outcome was, however, in one way quite different from what was expected.

While the issues brought up in advance became recommendations on the margin, the main output was that the international interest should include more on health effects and particularly those from small particles. In this connection, the expert from the European Commission, announced the Commission’s upcoming work on an air pollution strategy “Clean Air For Europe – CAFE”. In fact, a lot of the discussions and the recommendations came to support the Commission’s initiative. Health now became a central part of the agenda whilst the ecosystems effects, although still an important part, received less attention. The European Commission also took, at least for some years, a leading position in the science – policy interactions, partly due to the focus on the CAFE strategy, partly since the GP didn’t enter into force until 2005.

4.2. Saltsjöbaden II

Several of the participants expressed their satisfaction with the first workshop and a couple of years later, Sweden and ASTA were approached with a request for a similar workshop. The Saltsjöbaden format was used again and from now on the workshops began to be called Saltsjöbaden workshops, although this one and all the following were organised in Gothenburg, far from Saltsjöbaden.

The key issue for discussions in autumn 2004 was the progress of the CAFE strategy, which now was approaching its end. Health effects from small particles in the air was a key issue for the European Commission, and discussions went along with the role of small particles including if a threshold for health effects could be set.

Some other issues were brought up. An expert from the US proposed at the workshop to set up a Task Force under the Air Convention to study the intercontinental transport of air pollution; a proposal that resulted in the establishment of the Task Force on Hemispheric Transport of Air Pollution (HTAP) at the following meeting with the Executive Body of the Air Convention. Another issue of importance at the meeting was the inclusion of greenhouse gases in integrated assessment modelling (27).

4.3. Saltsjöbaden III and IV

In 2007 it was time for the third workshop. The European Commission had now become a key stakeholder together with the Air Convention. From the Commission’s perspective the ideas behind the upcoming “energy and climate package” were brought up for discussion and much of the discussions were focused on how to combine air pollution and climate change mitigation policies. Even if there was a strong support from the workshop on including air pollution, the idea failed within the EU, and air pollution was hardly named in the package from 2008. Another issue that emerged at the workshop was that some atmospheric pollutants (particularly soot) could significantly contribute to increased temperature and that specific control actions could suppress the temperature increase. This idea became the start of a new area of activities.

5 Martin Lutz (Germany)
6 Bill Harnett, (United States)
Nitrogen in a wider sense than as an atmospheric pollutant was also emerging as an issue. Several scientific initiatives were taken, such as the EU project NitroEurope and key scientists were looking for a link to the Air Convention. In dialogue with key scientists from NitroEurope and other nitrogen-related projects, it was concluded that the Saltsjöbaden workshop was a suitable occasion to bring up the issue and discuss how a policy link could be formed for the nitrogen projects. The outcome from the workshop was a recommendation to the Air Convention to set up a Task Force with a focus on nitrogen issues (28). The Convention followed the recommendation, and the Task Force on Reactive Nitrogen (TFRN) has since then been an important body for considering the nitrogen issue, not only as an air pollution problem but also as an issue with much larger dimension, e.g., through considering its role in the food production chains and dietary issues.

Then it only took two years until the next Saltsjöbaden workshop. This workshop was organised in October 2009 as an input to the upcoming United Nations Framework Convention on Climate Change (UNFCCC) Conference Of Parties (COP) in Copenhagen. Since the workshop was held under the Swedish EU presidency, the event became part of the official programme under the presidency. The air pollution - climate interactions was the obvious theme of the workshop. One main topic was the short-lived climate pollutants (SLCF), an issue that had emerged since the previous workshop (29). The conclusions were brought forward to the COP15 as a side event organised by US EPA. The SLCFs have since they were highlighted at the Saltsjöbaden workshops and the GAP forum 2008 (30) been a top issue within the Air Convention and elsewhere. A particular body, Climate and Clean Air Coalition (CCAC) has taken a role highlighting the issue and forming implementation processes for the SLCFs.

4.4. Saltsjöbaden V and VI

After the Gothenburg protocol was updated in 2012, it was again time for contemplating what the next steps towards better air quality should be. The new agreements urged for activities on the implementation, not the least how to involve the EECCA countries. Communication and reaching out to the areas outside the Convention were two other issues that were discussed. Sweden, with support from the Nordic countries, therefore organised a fifth Saltsjöbaden workshop in 2013.

Among the recommendations there was also one that urged the organisers to approach the International Law Commission (ILC) to bring up air pollution as an issue for an international law (31). The ILC was at that time already initiating work aimed at forming a fundament for an international law for protecting the atmosphere in a similar way as the already existing Law of the Sea. The special rapporteur for this work, saw the value of having a scientific support in his work and invited experts from the “Saltsjöbaden community” to several annual sessions of the Commission to give presentations and discuss the prospects of a law. The work is finished from the Commission's side and put forward within the UN system.

The issues of broadening the scope and collaboration on air pollution was the theme for the 6th and latest of the Saltsjöbaden workshops. The earlier focus on transboundary issues on a

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7 Mark Sutton (United Kingdom) and Jan Willem Erisman (The Netherlands)
8 Shinya Murase (Japan)
continental scale was widened both inwards and outwards. Outwards, there were sessions on how international organisations such as UNEP, WHO, WMO and others could work together with the Air Convention and take advantage of the experience from each other and work for a more global approach. As an outcome of the workshop the Executive Body of the Air Convention at its meeting in December 2019 supported the launch of a Forum for International Cooperation on Air Pollution (32).

To increase the interest among the EECCA countries, experts from these countries were invited to the workshop, and plenary sessions were simultaneously interpreted to Russian. One working group session was also directed to obstacles and opportunities for a more active participation in the legal instruments under the Convention. The progress of these activities has recently been presented in a UNECE report (33).
5. KEY SCIENTIFIC ACHIEVEMENTS UNDER THE PROGRAMMES

Introduction

The scientific research and understanding of cause-effect relationships have undergone a dramatic development since the millennium. The Gothenburg Protocol was, e.g., based on a coarse (50 km) deposition grid system and trajectory models for the source - receptor relationships. The shift to Eulerian models was a significant development resulting in increased accuracy in relation to meteorology and atmospheric chemistry. The knowledge on health effects has in the same way developed; epidemiological studies have shown much stronger evidence on the importance of air pollution for mortality. In addition, the role of atmospheric pollutants for climate change, not the least in the Arctic, has developed over the last 10 years. Our research has focused on areas of significant importance for the general understanding of air pollution and for obtaining a solid base for the NEQOs as well as for international policies.

The research programmes have formed a continuity, where research activities often have been linked between programmes. In addition, several of the key scientists have been involved in periods covering several programmes. This continuity has enabled analyses of long-term trends and experiments, which are fundamental for knowledge on air quality effects (BAMSE – cohort studies, deposition trends etc.), and formation of new expertise areas (Integrated Assessment Modelling), as well as harmonisation of methods and measurement techniques.

Since the research programmes have had a problem-oriented organisation, the needs of working across academic disciplines has become a key. For the health effects, close collaboration has been established between clinical researchers, epidemiologists researching dose-response relationships, and atmospheric scientists working on source receptor relationships. This type of transdisciplinary research also holds for the studies of environmental and economic effects. Close collaboration has also been established between Swedish institutions working within the same discipline, e.g. medicine and epidemiology, ecosystem effects, atmospheric chemistry and dispersion modelling etc. The sections below present some background and the most significant research results together with results from other studies and examples of their role for policy. With a couple of exceptions, all the results presented are based on some, but varying, involvement of the ASTA, SNAP, SCARP, CLEO or SCAC research programmes. In the cases where there the programme contribution has been significant and clearly stated in the original publication or in the annual programme reports it is indicated by reference to the programme in question.

SUPPORTING NEW KNOWLEDGE

>300 peer reviewed articles,
>10 book chapters,
>50 reports

Guest editors to special issues in:
- Ambio Vol. 34 iss. 1 (2005),
- Ambio Vol. 38 iss. 8 (2009),
5.1. Improvements in human and ecosystem air pollution exposure calculations

- Emission trends for most pollutants are mirrored in trends of decreasing concentrations of air pollutants,
- The future climate penalty on air pollution is weaker than the impact of emission decrease in Europe,
- Different risk estimates should be applied depending on the spatial scale for PM exposure. This results in higher risk estimates from sources within a city than for long-range transport contributions of particles, which may be critical when comparing health benefits of different abatement strategies.

5.1.1 Historical mapping and source attributions

Anthropogenic emissions of nitrogen oxides and sulphur dioxide have decreased in Europe since the 1980 and the 1970s respectively (34-36). The historical modelling studies within CLEO showed that this emission decrease has resulted in less atmospheric deposition of nitrogen and sulphur in Europe and Sweden. The modelled evolution corresponds well to the observed (34, 35). Researchers in SCAC contributed to an ensemble of European CTMs in an initiative under the TFMM (37). Decreasing trends in deposition were predominantly observed at European measurement sites during 1990-2010 for wet deposition of oxidized and reduced nitrogen (38). However, the ensemble of models showed weaker trends than the observations for the same period.

A data set compiled through an approach termed measurement-model fusion, with input delivered by high-quality observations and time-consistent modelling, form the basis for a so-called re-analysis. Such data sets were produced partly in the framework of SCAC, using the MATCH Sweden system, for ozone (39) and deposition of nitrogen and sulphur (36). The deposition re-analysis was also used in SCAC to calculate a nitrogen budget for Sweden as well trends in deposition. The amount of nitrogen deposited in Sweden in 2015 (160 kt) mainly originated from other countries (139 kt). About 75% of the Swedish national emissions of 90 kt were transported to other countries. The ecosystems that received the largest amount of nitrogen during 2015 are spruce and pine forests (27 and 24% respectively), followed by marine and freshwater ecosystems (21%) and agricultural lands (11%). Since the 1980s, nitrogen deposition has decreased by 30% in Sweden (Figure 1). The decrease is statistically significant.
Research in the CLEO and SCAC programmes has demonstrated long-term changes in the ground-level ozone concentrations in northern Europe, based on analyses of observations alone as well as re-analyses representing 1990-2013. Analysis of different fractions of the concentration range, expressed as percentiles, demonstrated that the highest ozone concentrations are decreasing, while the lowest concentrations are increasing (39, 41). Furthermore, SCAC and CLEO contributed to results showing that in northern Europe there is a shift in the time of year when the highest ozone concentrations occur, towards higher concentrations during spring (39, 42). Hence, ecosystems and humans have become more subject to “chronic” exposure of medium-range ozone concentrations, while high ozone peaks have decreased. Simultaneously, the start of the vegetation growing season has shifted towards earlier dates in the year. Combined, these changes potentially may increase the ozone exposure of northern vegetation, but if both the timing of the spring ozone peak and the onset of the growing season shift at the same extent this will not necessarily be the case. However, the extended ozone season may have increased human health impacts for people performing winter sports at far northern latitudes. On average, ozone concentrations in Sweden have decreased in summer, but springtime concentrations have risen and occur earlier in the year in northern parts of the country. This pattern of development is due to

1. decreasing precursor emissions in Sweden and Europe,
2. increased Asian emissions impacting through inter-continental transport, and
3. a changed climate (39, 43).
The last point includes increasing ozone uptake by vegetation in May, which could result in larger impacts, due to the earlier start of the growing season. Multi-model studies from the ED Trends project verify that these model estimates are robust and perform well in comparison to observations across Europe (44).

SCARP research showed, based on 1997-2010 background observations and backward trajectories, that the concentrations of PM$_{2.5}$, soot and ground-level ozone were 4.0, 6.8 and 1.3 times higher, respectively, in air masses from the southeast Europe compared to air from the southwest (45).

In several epidemiological studies, starting with Jerrett, Burnett, et al. (46), it has been shown that resolving spatial variations of PM$_{2.5}$-concentrations within cities results in higher risk estimates. This tendency has been observed down to scales < 1km (47). For emission sources resulting in strong and persistent concentration gradients, such as major roads, even higher spatial resolution (<100 m) are likely to add important information for epidemiological analyses. Based on these assumptions, air pollution exposure with a spatial resolution down to 50 m was applied in the SCAC programme, allowing a detailed classification of traffic related PM exposure for the years 1990-2011 in Stockholm, the counties of Västra Götaland and Västerbotten (48). This is a significant achievement, considering the large geographical areas and long time periods that were analysed. A conclusion from work within the SCAC-programme is that different risk estimates should be applied depending on the spatial scale of the exposure data (49). Such practice results in higher risk estimates for sources within the city than for long-range transport contributions and may be critical when comparing health benefits of different abatement strategies. Estimates of health effects from air pollution made by Swedish authorities currently rely on risk estimates adjusted for spatial scale (5, 50).

The question of sources and chemical composition is strongly linked to corresponding health impacts of particles. Although the evidence for health impacts from particulate matter (PM$_{10}$ & PM$_{2.5}$) smaller than 10 and 2.5 µm in diameter is strong, the question whether there are certain types of PM that are more harmful than others still eludes the research community. Despite consensus that there most probably are differences in toxicity, current standard methodology for health impact analysis (51), applied for example by EEA, recommends using the same risk estimates for all types of PM$_{2.5}$. This recommendation is mainly caused by difficulties in separating effects from different pollutants statistically due to highly correlated exposures from different sources. For Sweden, a clear example of this is caused by use of studded tires, resulting in emissions from road surface wear that are often larger than the engine exhaust emissions. The composition of PM$_{2.5}$ from road wear is very different from the composition of exhaust PM$_{2.5}$, but there is still no clear evidence to support the use of different risk functions when estimating the heath impact. There is an obvious risk that the current generalizations result in ineffective regulations and abatement measures. Increasing the precision and accuracy in source-specific exposure estimates, such as residential wood combustion (RWC) and road traffic, could potentially help to statistically separate health effects caused by different sources and add another piece to the puzzle.

In the SCAC programme, an aim was to describe source-specific exposure for traffic exhaust PM and road wear PM, shipping, RWC and other sources. Traffic related air pollution as a
whole was described with sufficient precision to allow source-specific health studies, but emissions from wear were estimated using a simplified methodology (48). Exposure due to PM from RWC is today comparable to exposure from traffic exhaust PM and the relative importance of RWC is likely to increase with the on-going electrification of the vehicle fleet. The emissions of PM from stoves and boilers vary dramatically depending on the type and condition of the heating appliance, the fuel quality, and on how the appliance is used. These varying factors and the lack of a national register of heating appliances, make exposure mapping for RWC with high spatial resolution challenging. In parts of Sweden, detailed inventories of heating appliances are available from chimney sweeper registers. In the SCAC programme, such data was used to describe PM exposure from RWC in the county of Västerbotten (48, 52) and has the potential to greatly improve precision and accuracy in exposure estimations. In the SCAC programme, further improving the description of PM exposure due to RWC was identified as top priority to improve the accuracy in urban human exposure estimates. Other identified potential improvements to exposure estimations are shipping emissions (53) and exposure due to emissions from industry and energy production.

5.1.2 Future air pollution: impact of emissions and climate penalty

The extreme air pollution summer of 2003 in Europe gave an indication that future climate change may cause a climate penalty on air pollution. At that time, long-term modelling efforts were conducted to analyse the impact of meteorological variations on air pollution (54, 55). The results showed a substantial impact of variations in meteorology on air pollution concentrations and deposition. This information was used to advise EMEP MSC-W on suitable years for the atmospheric modelling in support of the initial attempt to revise the NEC Directive in 2005 (56). The regional climate modelling developed at the SMHI Rossby Centre gave atmospheric chemistry modelers within the ASTA programme at SMHI early access to climate model output enabling an extension of the work on meteorological variability on air pollution into climate change impacts, e.g. Langner, Bergström, et al. (57). In SCARP the sensitivity to climate change and the significance of specific processes involved was studied (58), showing that climate impact on isoprene emissions and stomatal conductance are important processes for future ozone exposure.

In CLEO, historical and future projections of European emissions were constructed. Emissions scenarios of anthropogenic NH₃ and NMVOC emissions were pointed out as specifically uncertain. The sensitivity to multiple climate scenarios as well as air pollution emissions scenarios were in SCARP and CLEO studied for ozone and deposition of sulphur and nitrogen in Europe and Sweden. Early studies showed increasing ozone concentrations in continental Europe due to climate change, while impacts in the north were weaker and more diverse (54, 58, 59). Future emission scenarios, with strong reductions projected for mainly NOₓ and SOₓ, induce a strong decrease in high ozone concentrations (figure 2) the vegetation ozone exposure index AOT40, and sulphur and nitrogen deposition until the mid and end of the 21st century, even when considering the climate penalty (59-61). Research made in both CLEO and the newer SCAC programme both suggest that a more realistic measure of the ozone effects than AOT40 can be described through the phytotoxic ozone dose (POD), which is not projected to decrease as strongly and not to decrease below the critical level (41, 62).
A meta-analysis of the climate penalty of ozone in an international collaboration with support from CLEO was shown to be robust in large parts of continental Europe until the end of the century (63). A Nordic model inter-comparison, also with support from CLEO, produced robust results showing that the main driver of future change in nitrogen deposition is emission reductions, but that the dry deposition magnitude and spatial pattern is largely uncertain both at present and in the future (64). Another successful international collaboration produced papers describing future scenarios of ground-level ozone, NO\textsubscript{2}, and particle mass (65-68). These papers were produced using modelling with multiple air pollution models in international collaborations, and the Swedish modelling had support from both CLEO and SCAC. International collaborations also produced scenarios for urban background ozone in Stockholm and Paris until 2050 (69). Another interesting example is that future ozone levels due to the climate penalty is projected to cause increased mortality in continental Europe but a decrease in the Nordic and Baltic countries (70, 71).

Low ozone concentrations have been identified to be sensitive to the evolution of hemispheric background ozone with potentially increasing ozone levels depending on future emissions mainly in Asia. SCAC research have contributed to the understanding that the hemispheric background ozone increase has levelled out in more recent years (40, 43). A SCAC study of the impact of the 2018 heat wave on observed ozone concentrations show a strong climate penalty (72), stronger than expected from the earlier model sensitivity studies. These results indicate that the currently established relatively weak climate penalty on ozone may in fact be underestimated. The cause for this underestimation is potentially missing processes and emissions in the CTMs (for example wildfire emissions), or climate models failing in capturing extreme conditions. Correspondingly, the programme identified the need for new studies with
improved resolution and updated climate and air pollution models. Another important future research area identified is the process of nitrogen dry deposition and re-emission (so called “compensation point”), which is still one of the larger uncertainties which needs to be revisited in future research projects. Better knowledge about this process might have a strong impact on both historical exposure mappings and future scenarios, especially in nutrient deficient areas, where the long-range transport is an important factor. Inclusion of a NH₃ re-emission may lead to improved estimates on deposition of nitrogen in remote, sensitive areas.

5.2. Air pollution and health effects

- Human experimental studies have elucidated the mechanisms of cardiovascular and pulmonary health effects of particle exposure.
- Epidemiological studies of long-term exposure to traffic pollutants and PM in Sweden within cities have shown associations with mortality and an increasing number of diseases.
- Health impact assessments show that particulate air pollution is the environmental health risk that causes the highest number of premature deaths.

5.2.1 Short-term effects

To explore the mechanisms of how air pollution affects human health, experimental chamber studies have been performed within SNAP with higher than ambient exposure levels. There are several important results from these SNAP studies. In Umeå, short-term exposure to diesel exhaust particles was shown to have rapid effects on the pulmonary immune system, and that the participants with asthma or COPD were most sensitive to these effects (73, 74). A series of ground-breaking trials showed marked effects on the cardiovascular system within hours of exposure, including an impaired ability to dissolve blood clots and regulate vascular function, increased arterial stiffness and myocardial ischemia (75-81). These findings provide potential mechanisms for the epidemiological associations between air pollution exposure and increased risks of myocardial infarctions (MI) or stroke (82, 83). The effects were associated with combustion-derived nanoparticles and reduced by particle traps, and the same cardiovascular effects were not observed for exposure to nitrogen dioxide or concentrated ambient particles (84-86). Standard treatment with cardiovascular medication did not protect against the detrimental effects of diesel exhaust particles. Co-exposure to ozone was found to enhance the inflammatory response of diesel exhaust (87). Exposure to diesel exhaust was also shown to induce changes in EEGs, indicating a cortical stress response (88).
In Gothenburg, starting within SNAP, the worlds’ first chamber studies of wood smoke exposure found increased biomarkers of inflammation, coagulation and possibly lipid peroxidation after exposure in healthy adults, indicating increased risks of cardiovascular events in the short-term and of the development of cardiovascular disease development of prolonged exposure (89, 90). Exposure to lower doses of different types of wood smoke was associated with symptoms and biomarkers of airway effects indicating effects on airway epithelial permeability and possibly airway inflammation, and DNA damage, but not with genotoxic effects, systemic inflammation and coagulation (91-93). In Umeå, effects on arterial stiffness and decreased heart rate variability after wood smoke exposure was found, indicating immediate effects on risk of cardiovascular events (94). Overall, wood smoke particle exposure could not be shown to be less toxic than exposure to diesel exhaust. The chamber studies stimulated other international chamber studies of diesel and wood smoke exposure. The research field in this is still ongoing, and a recent review of the 12 chamber studies performed so far concluding that further carefully conducted human exposure studies with repeated exposures and outcomes are needed (95).

Short-term effects of episodes with higher air pollution exposures have also been shown in a number of studies. A study of the effects of PM exposure from raging wildfires in Russia within SCARP combined with a prolonged heat wave showed an excess of 11000 deaths from non-accidental causes in Moscow during the summer of 2010, mainly among those older than 65 years, highlighting the importance of considering the interaction between high temperatures and air pollution exposure in risk assessments (96). Effects of short-term exposure on clinical events have also been shown in Sweden in studies with support from SCAC. Episodic high ozone concentrations in the Stockholm region have in several studies been associated with an increased number of deaths. In a study over 20 years, an increase in number of deaths of 1.7% per 10 μg/m³ increase in the daily 8-hr max of PM₁₀ was observed among those with a previous acute MI, which was more than three times higher than those with no previous MI (97). Also, PM₁₀, especially the coarse PM fraction (PM₁₀-₂.₅) and road dust, has been linked to an increase in daily deaths (98, 99). With support from SNAP, a case-crossover study of patients with ICD (implantable cardioverters defibrillators) found associations between short-term (2 hours, and 24 hours) exposure to PM₁₀ and ventricular arrhythmias (100).

Other studies within SNAP and SCARP have focused on subclinical markers. The relations between short-term exposures to O₃, NOₓ, and PM₁₀ and proximal and distal airway inflammation, measured as fraction of exhaled NO (FENO), were studied in randomly selected adults in Gothenburg (101). An increase in the 5-day average O₃ levels was associated with an increased level of FENO from the distal airways, while an association was less obvious for inflammation of the proximal airways. In controlled experiments, mild asthmatics exposed for 2 hours in a road tunnel to 80 μg/m³ PM₂.₅ exhibited increased symptoms, decreased peak flow
and signs of inflammatory response in the upper airways, which further emphasizes that asthmatics are a vulnerable group to common air pollutants (102).

A European multicentre study with Swedish participation also found that fibrinogen genes modified the associations between PM exposure and fibrinogen levels (103). And in a SCARP panel study of healthy 11-year-olds in Umeå during April–June when levels of road dust and birch pollen usually peak, multi-pollutant models found associations between coarse PM and an increase in FENO indicating airway inflammation (104).

5.2.2 Long-term effects
Several studies have shown associations between long-term exposure to the relatively low levels of air pollution in Sweden and mortality rates, as well as other health effects such as cardiovascular diseases (CVD), dementia, diseases of the lungs, and pregnancy outcomes. A cohort study of men in Gothenburg over a 35 year time-period found an association between long-term residential NOx exposure and natural mortality (105). A SCAC study of residential exposure to long-term PM in cohorts from Stockholm, Gothenburg and Umeå also found associations between both PM10 and soot and natural mortality, with 17% and 9% increased risks per 10 µg/m³ and 1 µg/m³ of lag1-5 exposure (106). These were high estimates in relation to the literature. Both PM10 and PM2.5 were associated with CVD mortality. Analyses of source-specific risk of PM-exposure and mortality will also be published.

Another SCAC study of nearly 187,000 births in Greater Stockholm investigated the associations between exhaust PM and O3 at home and birth weight (107). A higher socioeconomic status was associated with higher residential exposure to exhaust PM, indicating the importance of adjustment for socioeconomic status. The associations between modelled levels of exhaust PM and birth weight were negative for all three of the studied exposure windows (i.e., first and second trimester and full pregnancy). The risk of being born small for gestational age increased with the level of exhaust particles in all three exposure windows. Studies conducted in the county of Scania in southern Sweden demonstrated associations of prenatal NOx exposure with pre-eclampsia and gestational diabetes in pregnant women (108).

Levels of PM2.5 from local residential wood burning and road traffic modelled in SCAC were associated with dementia incidence in a cohort from Umeå, where an association with NOx from a Land Use Regression (LUR) model before had been shown (52, 109). Study participants with an address in an area with the highest quartile of PM2.5 from residential wood burning and who also had a wood-burning stove at home were more likely to develop dementia than others.

The first Swedish study to provide support for an association between long-term air pollution exposure and fatal cardiovascular disease in 2006 was a SNAP study which found a statistically significant effect between modelled NO2 at the home address and out-of-hospital fatal MI in middle-aged people in Stockholm county (110). In another study from Stockholm, increases in biomarkers of systemic inflammation were associated with long-term exposure to traffic- and heating-related air pollution, rather than short-term exposures (111). These associations, as well as the association between air pollutants and MI in the same cohort, were in the SCARP programme found to be affected by genetic susceptibility (112). In a cohort from Gothenburg, a case-control analysis found an increased risk of acute MI associated with residential NO2
exposure, with suggested interactions with genes associated with oxidative stress (113). In two Gothenburg cohorts studied within the SCAC programme, associations of were found between PM exposure and ischemic heart disease (IHD) and stroke (114). The associations tended to be stronger for women, non-smokers, and in higher socioeconomic classes. In a recent SCAC meta-analysis of long-term PM exposure of four cohorts from Gothenburg, Stockholm and Umeå, no associations were found between total levels of air pollutants and IHD incidence, but positive associations for soot exposure and stroke (115).

In a series of publications funded by SCARP and based on a birth cohort from Stockholm, residential exposure to air pollution during the first year of life was associated with allergic sensitization to pollen, decreased lung function, as well as increased risk of asthma up to school age and adolescence (116-122). Most recent results show that early-life air pollution exposure can increase the risk of chronic lung disease even up to 24 years of age, e.g. chronic bronchitis and irreversible airflow limitation (123, 124). Exposure after the first year of life seemed to affect the children's health less than that during infancy. Further, exposure to air pollution during the first year of life was related to increased levels of markers of inflammation (the markers interleukin (IL)-6, -10, -13, and TNF-α) in children (125). In addition, interactions between air pollution and inflammatory and oxidative stress genes, as well as genes, that have previously been linked to lung function and chronic obstructive pulmonary disease, have been identified with SCAC contributions (126, 127). In a cohort from Gothenburg, exposure to traffic particles was associated with reductions in the lung function indicators 'forced expiratory volume in 1 second' (FEV1) forced vital capacity (FVC) and (FVC) and increased risk of subnormal values (128). A SNAP study of respiratory health cohorts in Umeå, Uppsala and Gothenburg found association between long-term exposure to vehicle exhausts and increased risk for new-onset asthma among adults (129), with increased risk for asthma remaining also in a joint European analysis (130-132).

The health impact of air pollution in Sweden is substantial. An impact assessment in 2005 estimated that long-range transported anthropogenic PM was associated with 3500 deaths per year in Sweden, and a smaller impact of the local sources (133). At the same time the researchers questioned the recommended use of uniform risk coefficients for health impact assessment (HIA) of PM regardless of the particle sources, since the literature increasingly supports assumptions that combustion-related PM is associated with higher relative risks, which may shift the focus for abatement strategies. However, SNAP research showed that also road dust and other particles in the coarse fraction show effects, especially on respiratory disease (134).

A more recent SCAC health impact assessment in 2017 described premature mortality from sectorial contributions to PM exposure with different exposure-response factors in Gothenburg, Stockholm and Umeå (48). In general, most of the PM2.5 exposure was due to long-range transport, while for soot, the local sources were equally or more important. The major part of the premature deaths was related to local emissions, with road traffic and residential wood combustion having the largest impact. This study emphasizes the importance of within-city concentration gradients of exposure. It also implies that control of local PM emissions may have a strong potential in abatement strategies. A recent SCAC publication showed with policy-relevant scenarios how important it can be to use source-specific exposure-response factors in HIA (49). The study showed that an HIA using source-specific exposure-response functions
would for some scenarios find 10 times higher number of premature mortality than if using a uniform exposure-response function. The difference is not homogenous over all scenarios, implying that the use of uniform or source-specific ERF can change the policy recommendation from the HIA.

5.3. Ecosystem effects of nutrients and acidifying compounds

- Politically, the strongest arguments to minimize the impact of air pollution on ecosystems are related to the damage to living organisms. Chemical parameters e.g. acidity of lakes or nitrate in groundwaters are, however, good indicators of damage to trees, fish, and other aquatic organisms or to red-listed plant species.
- Emissions of sulphur have declined strongly. At present about 4% of the European ecosystems receive more acidifying deposition than they can tolerate (deposition exceeds critical loads). The decline in emissions and depositions has been followed by widespread recovery from acidification.
- Emissions of nitrogen have declined to a lesser extent and about 58% of European ecosystems have deposition in exceedance of their critical load for nitrogen as a nutrient. Eutrophication of soils and waters is currently the biggest air pollution threat to European ecosystems.

5.3.1. Effects of sulphur and nitrogen deposition

Effects of S and N deposition on ecosystems can be divided into two broad categories: chemical and biological effects, with multiple links between the two. Typically, biological effects are of key interest. These could be, e.g., forest health, plant species biodiversity or abundance and health of fish and other aquatic organisms in lakes and streams. These are issues engaging a broad range of stakeholders and therefore generate will for change and provide politically powerful arguments needed to motivate measures to limit emissions of air pollutants.

The chemical effects, such as acidity of a lake, loss of base cations from soil, nitrogen content of foliage or nitrate concentration in groundwater, are more difficult to relate to for people not working with these issues or otherwise not particularly interested. Chemical parameters have, however, the great advantage that they are relatively easy to measure.

A chemical analysis of one lake water sample reveals a lot of valuable information about the lake's chemical status, which correlates with fish population health.

To investigate the fish population directly would provide even better information, but at a much higher cost of sampling, analysing, and interpreting the data. The situation gets even more complicated with the air pollution effect on biodiversity. To document a decrease in abundance of red-listed, often oligotrophic, plant species due to

The Gårdsjön Roof project included covering 6 300 m² of forest with a roof (below the tree branches). Data from this project provided plenty of input to Swedish and international research during the early 2000.
increased atmospheric deposition of nitrogen requires repeated plant species surveys over long time, and thus both significant time and resources. To measure the chemical status of the soils either directly by soil sampling or indirectly by the sampling of groundwater or runoff draining the soils is again much easier. Another advantage of chemical parameters is that these are – relative to biological parameters – easier to model with mathematical geochemical models. Models also provide an opportunity to look back in time to see what the ecosystem status used to be, and to explore possible futures under various air pollution scenarios. Nevertheless, it is the impact in living organisms which is the goal of investigations of air pollution effects on ecosystems, even though the means to investigate these impacts typically is through looking at chemical parameters.

Another factor that needs to be kept in mind is that both nitrogen and sulphur are essential nutrients that can, especially in case of nitrogen, under natural conditions be growth limiting. Additional reactive nitrogen (Nr) input from air pollution can therefore have growth stimulating effect, which often is positive. Most importantly, additional Nr input may increase primary production of food and material and thus carbon sequestration, and increased growth may mean enhanced supply of provisioning ecosystem services. The difficulty is, however, that air pollution is deposited on all ecosystems, which in many cases means ecosystems where increased growth is not desirable. In addition, the deposition input of Nr is in many regions in excess to what is beneficial from any point of view.

The negative air pollution effect on ecosystems includes freshwater acidification leading to damage or even extinction of acid sensitive aquatic organisms at the impacted areas. Soil acidification leads to a toxic environment for fine roots of plants, mycorrhiza, and other soil organisms. Eutrophication could in turn cause a whole sweep of negative effects including loss of N-sensitive plant species, shift in plant species towards more graminoid and less forbs, algal blooms, ground- and surface water pollution with nitrate, increased emissions of methane or – after initial growth stimulating effect – even decrease in growth if the Nr input is in excess to what the combined ecosystem demands.

5.3.2 Critical loads
To bridge the gap between the biological and chemical effects of air pollution, and also between tolerable (or even beneficial) N and S input from damaging deposition and input, the concept of critical load (CL) was developed. A critical load can be defined as “a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge” (135). The application of CLs includes choosing what part of an ecosystem, or what organism or group of organisms, should be protected, defining chemical criteria of damage to the biota, and establishing the numeric threshold of the chemical criteria. Criteria frequently in use are e.g. the BC/Al ratio in soil (as a measure of toxicity to fine roots), and NO$_3$ concentration in the leachate from the soil (high concentrations would cause polluted groundwater or eutrophication downstream or inorganic Al concentration at levels toxic to fish). More recently, undesirable changes to plant species composition are for decision support purposes quantified as a change in the Habitat Suitability Index (136). After deciding which part of an ecosystem that should be protected and defining a damage indicator, the task is reduced to quantifying the maximum atmospheric deposition under which the damage criteria is not violated, i.e.
calculating the CL. For that purpose, the methodology is described in in the critical loads Mapping Manual developed by the ICP on Modelling & Mapping under the Air Convention (137).

5.3.3. Acidification

Acidification of surface waters and catchment soils due to air pollution is an environmental problem which has been on the political, scientific, and public agenda for more than 50 years. It is also one environmental problem where a major success of alleviating – and in many areas even solving – the problem is undisputable. Key milestones on the way were the recognition of the causal relationship between emissions, long-range transport and ecosystem damage, recognition of the mechanisms of damage to biota (to fish and to trees), finding links between biological damage and measurable chemical parameters, setting up an international convention to combat air pollution and using critical loads to map the situation and the progress (14). Another important success factor has been the visibility of damage in form of disappearing fish population from Scandinavian lakes or damage to foliage of trees in Central Europe, which provided rationale for political momentum. European emissions of SO$_2$ as the major pollutant causing the acidification has been declining for three decades (138) and European ecosystems have experienced widespread recovery for nearly as long (139). The computed area at risk of acidification due to exceedance of critical loads is currently covering only about 4% of the ecosystems (2.9 million km$^2$) in Europe (136). That does not mean that recovery from acidification has been complete. Many of the acidified soils lack mechanisms to recover and will remain damaged for the near future, but it does mean that air pollution has been reduced to levels that do not cause further damage and that recovery – fast or slow – is ongoing.

5.3.4 Eutrophication

Compared to acidification, air pollution related ecosystem eutrophication is decreasing at a far slower pace. Currently, about 58% of European ecosystem area considered for calculating critical loads for nitrogen as a nutrient have exceedance of critical loads and are at risk of ecosystem damage (136). The reasons behind this are twofold; emissions of reactive nitrogen are not decreasing as fast as emissions of SO$_2$ and secondly the ecosystem reaction to changing input of N is complex involving a number of other factors such as site deposition- and land use history or climate change. As an example, the ASTA programme found, that the biotic interactions between plants and the herbivores and pathogens that attack and damage them, are influenced by nitrogen enrichment. Generally, increased nitrogen supply resulted in increased damage on plants from herbivores and pathogens. In turn, this triggered drastic changes in plant species composition of the vegetation. Nitrogen induced vegetation changes occurred at lower levels of nitrogen enrichment than previously anticipated. Also, vegetation responses differed depending on whether reduced or oxidized nitrogen was added.
5.4. From ozone concentrations to leaf uptake – plants breathing ozone-polluted air

- A physiologically more relevant ozone exposure index for vegetation was developed, based on leaf ozone uptake: the Phytotoxic Ozone Dose (POD)
- The POD index takes into account how the different climate conditions promote leaf ozone uptake across Europe, resulting in relatively increased risks for vegetation damage in northern Europe
- Analyses of the heatwave in the summer 2018 revealed the potential interaction between ozone concentrations and climate change, where reduced ozone deposition towards the vegetation during drought may result in significantly higher ozone concentrations in the atmosphere

Vegetation may, compared to humans, be perceived as passive organisms, just sitting there hoping for the best. However, plants adapt to the environment to a very significant extent, both by altering their growth pattern in relation to prevailing environmental conditions, and by short-term physiological adjustment to weather and other circumstances. Especially the latter aspect has turned out to be of utmost importance in plant toxicology. Continuous research within the ASTA, SCARP, CLEO, and SCAC programmes has contributed to a shift in the methodology for how to quantify vegetation exposure to ozone, starting with the concentrations in the air and ending up with a more physiologically relevant method to estimate the amounts of ozone molecules that damage the plants by entering the leaf interior through microscopical pores on the leaf surface: the stomata.

5.4.1 Establishing determinants of when ozone damages vegetation

In the case of humans, it is obvious that inhalation of air, potentially containing harmful levels of air pollutants, is highly significant. Intensified physical activity will increase the gas exchange and thus the dose of these pollutants. In plants, the range of gas exchange rates between the leaves and the surrounding atmosphere is very large, larger than in humans and many animals. Leaf gas exchange is controlled by the stomata, pores that plants have in large numbers on their leaf surfaces. The plants can open and close the stomata. The degree of stomatal opening is known as the stomatal conductance. Open stomata permit carbon dioxide to enter the leaf interior and be assimilated in photosynthesis. This comes at a price: inevitably water vapor will be lost from the stomatal pores when they are open. An additional aspect is that gaseous toxic pollutants, such as ozone, are absorbed to the leaf interior through the stomata, as exemplified by the measurements shown in Figure 3. The stomatal conductance shown in the upper panel was calculated from measurements of transpiration and leaf temperature using a conventional gas exchange methodology. In parallel, the lower panel shows the stomatal ozone uptake as estimated from the ozone concentrations measured in the airstream before and after passing the cuvette. The leaf was left in a cuvette overnight in darkness and low intensity white light was turned on in the morning, as indicated
by the first arrow. Light intensities were increased at the second arrow. The leaf was then cut outside the cuvette at the third arrow to induce desiccation of the leaf and hence stomatal closing. The ozone concentrations in the cuvette were kept constant at 40 ppb. For details of the measurements, see Karlsson, Pleijel, et al. (140). When the stomata are closed the leaf ozone uptake is very small. It is well established that the toxic effect of ozone is related to the stomatal ozone uptake, while deposition to the exterior surfaces of the leaves is of minor importance for damage.

![Graph](image)

*Figure 3: An illustration of the close connection between stomatal conductance and the rate of stomatal ozone uptake for a wheat leaf.*

The stomatal conductance is highly dynamic. On the large geographical scale, climate conditions during summer with long daylight hours, high air and soil humidity promote high stomatal conductance and hence high leaf ozone uptake. These are conditions that prevail in northern Europe, while in contrast the summers in southern Europe are characterized by dry air and soil, and thus less ozone uptake.

5.4.2 Developing a new index for ozone damages to vegetation

By the mid-1990s, a discussion emerged on the lack of sensitivity to environmental variables in ozone risk assessments for vegetation in Europe. The variation of ozone uptake by vegetation under different weather conditions was highlighted and implications of the observation of smaller effects of high ozone levels on crops with limited water availability compared to well-watered was discussed. Initiatives were also taken to develop models for stomatal opening in different conditions. However, it was only at the turn of the century that the first systematic attempts were made to combine the stomatal conductance modelling with experimental data on
ozone effect on plants. By merging these two aspects, it was possible to derive empirically well-founded response-relationships based on the physiological uptake of ozone. In addition, it could be shown that the apparent variation in observed effects in different sites, years and experiments declined when the ozone uptake-based approach was applied. This was a result of the environmental variables on leaf ozone uptake explaining a substantial part of the variation in response. Based on these considerations, important first steps towards a physiologically relevant dose measure for ozone, were treated at a workshop in Gerzensee, Switzerland, in March 1999, with key contributions from Swedish researchers funded by the ASTA programme. Much through active Swedish research and hosting of workshops, funded by the ASTA and CLEO research programmes (see chapter 6.2), a new metric that better represent leaf ozone uptake has been developed: the Phytotoxic Oxone Dose (POD).

The use of POD in risk assessment has a number of implications as compared to assessments based on concentration-based exposure indices like AOT40. From a geographical perspective, the significance of contrasting climates of different regions for ozone exposure becomes apparent. Humid areas with modest temperatures, like many areas in western, central and northern Europe, provide favourable conditions for efficient leaf ozone uptake. Dry climates with high temperatures, such as the Mediterranean, and south-east Europe, on the other hand, promote stomatal closure, which will limit plant ozone uptake. Although the warm and dry climates often have much higher ozone concentrations than cooler and humid ones, the difference in POD-based ozone exposure is smaller than what concentration-based exposure indices suggest. The difference between the ozone exposure estimated for deciduous forests across Europe, depending on if the AOT40 or the POD concepts are used, is illustrated in Figure 4. When the AOT40 concept is used, a much higher forest ozone exposure is estimated for southern compared to northern Europe. When the POD concept is used for the same period (Figure 4b) the difference between the southern parts of the Nordic countries and southern Europe becomes much smaller. Hence, the relative significance of ozone impacts on vegetation between northern and southern Europe shifts considerably when moving from AOT40 to POD.
Figure 4; Ozone exposure of deciduous tree species estimated with the EMEP model. (A) Exposure estimated as AOT40 April–September, an ozone exposure index based on ozone air concentrations; (B) Exposure estimated as the stomatal ozone flux (AFst1.6, an index used earlier but equivalent with the POD concept). For further details of the modelling, see Karlsson, Pleijel, et al. (140).

Furthermore, the POD-based approach makes possible a dynamic assessment of the influence of climate change on ozone exposure, which is not possible using exposure indices like AOT40. Where future climate is becoming more humid, the risk for ozone effects on vegetation will increase, provided ozone concentrations remain similar, since stomatal ozone uptake is facilitated. This means that the risk for effects of ozone on vegetation may increase even if emissions of ozone precursors do not increase. Areas becoming dryer will likely experience a smaller ozone uptake by plants having their stomata to a larger degree closed, to avoid drought stress.

Research supported by SCAC studied more details of ground-level ozone concentrations. A significant interaction between the concentrations of ground-level ozone, meteorological conditions and vegetation can be exemplified by the conditions during the heatwave of 2018. In addition to a certain degree of promotion of ozone formation by the warm and sunny weather, the smaller deposition to vegetation in the dry conditions likely contributed significantly to the enhanced ozone ground-level concentrations in this year. Less uptake by the plants resulted in higher concentrations of ozone in the lower atmosphere. This is yet another example of the importance of stomatal control of ozone effects on vegetation, which has implications for the
plant health effects of this pollutant. Possibly, heat waves of this kind will become more common in a future world of altered climate.

In more recent years, the POD approach to derive response functions for ozone effects on vegetation has included new crops (e.g. tomato), been adopted in further regions (e.g. China and India), and covers vegetation types like species of semi-natural vegetation not originally considered.

To this date, all ozone molecules that are taken up to the leaf interior are considered to have equal negative impacts on plant metabolism by the current POD approach. However, plants have considerable antioxidant capacities. It might be the case, that ozone molecules that are taken up to the leaves under certain environmental conditions have more negative impacts compared to other conditions. A further development of the concept of leaf ozone uptake would therefore be to consider quantitatively the ozone detoxification capacity of the leaf in the exposure index. First attempts to study this have been initiated.

5.5. Short-Lived Climate Forcers (SLCF), and climate change

- Reduced emissions of sulphur at mid-latitudes lead to increased heat transport in the atmosphere into the Arctic and an increased warming of the Arctic, while reduced emissions of soot lead to reduced heat transport and cooling,
- A reduction of soot emissions in any of the four different regions, North America, Europe, East Asia and South Asia, will result in a 3-5 times larger Arctic temperature change per unit mass compared to a reduction of sulphur emissions,
- The emission reductions of sulphur between 1990 and 2010 have caused a warming of the Arctic comparable with the warming by increasing CO$_2$ concentrations during the same period,
- Model-observation biases for SLCFs are larger in the Arctic than elsewhere, which emphasizes the need for model improvements,
- Model-observation and observation-observation comparisons of different cloud properties show large discrepancies, emphasizing the need for further work on both observations and models.

Starting from the CLEO programme, research activities with a focus on the links between air pollution and climate change were initiated. This effort was prompted by the increasing awareness of the importance of these links from both a scientific and policy perspective. The influence of sulphate and soot on climate was already discussed in the third IPCC report in 2001 (141). Their relatively short lifetime in the atmosphere later led to the concept of Short-Lived Climate Forcers (SLCFs). The concept Short-Lived Climate Pollutants (SLCPs) only refers to SLCFs that warm the climate, e.g., soot and methane. However, pollutants are often emitted from the same source, meaning that targeted reductions of some SLCFs will affect the other SLCFs, e.g. organic carbon (OC) and NO$_x$, are always co-emitted with soot.

Studies by AMAP, Bluestein, et al. (142) and UNEP and WMO (24) put the light on potential co-benefits between air pollution mitigation and climate change, i.e. of reducing warming SLCFs (such as soot, methane and ozone precursors) and at the same time improving air quality.
However, other major air pollutants including sulphates, nitrates and organic carbon cool the climate, which complicates potential co-benefits between mitigation of air pollution and climate. Large-scale atmospheric modelling research focusing on the links between air pollution and climate was not very articulated in Sweden at the time. With support from SCAC and in collaboration with the Norwegian Meteorological Institute in Norway, research activities focusing on interactions between air pollution and climate using the Earth System Model NorESM (143) were built up at Stockholm University. At SMHI a hemispheric version of the CTM MATCH was set up to study long-range transport of air pollution across the northern hemisphere. An offline coupled model system MATCH-SALSA-RCA4 (137) was also developed at SMHI where a high resolution CTM with detailed aerosol dynamics was coupled to a regional climate model over the northern hemisphere in order to study aerosol-cloud-climate interactions. The region in focus for these modelling activities was the Arctic, given the rapid climate changes seen there, its proximity to Scandinavia, and Sweden being a member of the Arctic Council.

5.5.1 Impact of past and future changes in sulphur and soot emissions on Arctic climate

An important finding from the modelling activities within SCAC is that the temperature response to an aerosol emission change outside the Arctic is largest within the Arctic, typically twice as large as within the emission region itself (144-146). Furthermore, the temperature response in the Arctic per mass unit emission change is about a factor three to five higher for soot (warming) compared to sulphur (cooling). This result implies that even though the global average sulphur emissions are about ten times greater than soot emissions, a large part of the climate effect (warming) caused by a reduction in sulphur emissions, e.g. to improve air quality, could be compensated by a corresponding smaller reduction in soot emissions (cooling).

In a subsequent SCAC study, Krishnan, Ekman, et al. (147) clarified the mechanism behind the enhanced temperature response within the Arctic. Reductions in sulphur emissions at lower latitudes, and the corresponding positive radiative forcing (less cooling), cause an increase in heat transport in the atmosphere from the middle latitudes to the Arctic. The increased heat transport initiates sea ice melt and a reduction in the Arctic sea ice extent, increased heat exchange between the ocean and the atmosphere, and thus enhanced warming. Changes in heat transport in the ocean were found to play a minor role and generally dampened the temperature response. The results show that models must represent the heat exchange between the ocean and atmosphere correctly and in particular the impact of sea ice changes on this turbulent heat exchange in the atmosphere.

Emission-to-temperature response metrics are intended for use in integrated assessment models to emulate the relation between regional emission changes and regional temperature change. In AMAP (148) and Sand, Berntsen, et al. (149), previously published response metrics for large latitude bands were used together with source receptor calculations for SLCFs (soot, OC, SO₂, O₃) from Arctic nation air pollution emissions to provide a corresponding country/sector/pollutant split of the metric for temperature change in the Arctic.

Using NorESM, Lewinschal, Ekman, et al. (146), and Sand, Berntsen, et al. (145) calculated emission-to-temperature-response metrics for sulphur dioxide (SO₂) and soot emission changes, respectively, in four different policy-relevant regions: Europe (EU), North America
(NA), East Asia (EA) and South Asia (SA). The emissions in each individual region were increased to give approximately the same absolute global average radiative forcing change (~0.45 Wm\(^{-2}\) for \(\text{SO}_2\) and below 1 Wm\(^{-2}\) for soot). Changes in sulphur and soot emissions in the different areas of the Northern Hemisphere (EU, NA, EA and SA) gave a similar temperature response per kilogram of emission change in different latitude bands (Southern Hemisphere, Tropics, Northern Hemisphere Mid-latitudes and the Arctic).

Preliminary (and yet unpublished) SCAC results also show that the temperature response from emission reductions in sulphur and soot within EU, NA, EA and SA are additive. However, the temperature response in the Arctic to an emission change in sulphur or soot is non-linear, i.e. the temperature change per kilogram of sulphur or soot becomes smaller if a large emission change is made - regardless of the emission region (145, 146). For the mid-latitudes, the temperature change per unit emission within the EU and NA is also non-linear while the result is less evident for the other emission regions. The non-linearity is most likely caused by a saturation in the indirect climate effect (i.e. the effect of aerosol particles on clouds) at high aerosol concentrations.

Funding by SCAC has also ensured a Swedish Earth System Modelling (ESM) contribution to the 2021 AMAP report (150). An important feature of these simulations is that climate effects are simulated interactively, including aerosol-cloud interaction and ocean/sea-ice feedbacks. Five ESMs, including NorESM, produced future climate projections for two different air pollution scenarios, one with maximum technical feasible reductions (MFR) in SLCFs and one with reductions according to current legislation (CLE). Both scenarios also include increasing \(\text{CO}_2\) concentrations according to the SSP2-4.5 scenario. The ESMs also consider climate feedbacks on natural particle emissions, such as dust and sea salt.

The ESM projections show that the Arctic will warm by approximately 1.6\(^{\circ}\)C between 2015 and 2050 if emissions follow a CLE scenario. Additional calculations show that increasing \(\text{CO}_2\) concentrations are responsible for 1.2\(^{\circ}\)C of this warming, while the SLCFs add approximately 0.4\(^{\circ}\)C to the Arctic warming, mainly due to decreasing sulphur emissions. Decreasing soot emissions cause less than 0.15\(^{\circ}\)C cooling which is counteracted by a similar warming due to increasing methane emissions. The projections also show that the MFR scenario will give about the same warming in 2050 as the CLE scenario, as strongly decreasing sulphur emissions are counteracted by decreasing soot and methane emissions.

### 5.5.2 Long-range transport and distribution of SLCFs in the Arctic

Arctic Haze, a yearly occurring air pollution phenomenon in the springtime Arctic, was first observed by scientists in the 1980s and has since then been closely monitored. These observations showed early on that the phenomenon is caused by long-distance transport of air pollutants originating mainly from the Eurasian continent. Long-term observations reveal strongly decreasing sulphate and soot concentrations during the winter period in the Arctic from 1980 to 2010. During the last 10 years, the trend has stagnated for soot and strongly slowed down for sulphate (150). These trends are important information for understanding interactions between Arctic air pollution and climate change. Comparisons of different observation sites in the Arctic show variability in trends depending on the closeness to open sea as well as nearness...
to remote and local sources, showing the necessity of a denser network of high-quality observations.

Atmospheric models are useful tools for projecting the future air pollution and climate based on different scenarios of emissions of air pollutants. It is important however, to understand how well models can represent reality in terms of observed chemical composition of the atmosphere. Such assessment efforts are usually labour intensive and require expert knowledge on different observations and is best carried out in international collaborations. Work on model evaluation in SCAC was therefore aligned with international assessment work including the POLMIP study focusing mainly on gases and ozone (151) and the AMAP assessments of soot and ozone (148) and SLCF (150). The work in AMAP shows improvement over time among model simulations of SLCFs in the Arctic. This is partly due to improved emission inventories for SLCFs and precursors including a better representation of seasonal variations. Model biases are however larger in the Arctic than elsewhere, and persistent model biases emphasize the need for future model improvements. Especially regarding the vertical distribution of SLCFs that are important for climate change. Several studies show that treatment of sink processes and vertical transport in clouds vary substantially between models (152, 153). Overall, the model intercomparisons in the upcoming AMAP 2021 report indicate that SLCF abundances in the troposphere both in the Arctic and globally are biased low. This suggests that overall impacts on climate from regions inside the Arctic may in these models be underestimated since impacts on the radiation balance are related to concentration changes in the atmosphere.

5.5.3 Aerosol cloud interactions in climate models

Clouds are important for Earth’s radiation budget and for the climate. However, clouds are difficult to simulate accurately in models and therefore represent one of the largest uncertainties in climate simulations. The simulation of cloud characteristics such as cloud water, cloud ice and cloud droplet number density are closely linked to the simulation of aerosols and microphysics in climate models.

In SCAC, SMHI developed an off-line coupled model system where the MATCH CTM with the SALSA aerosol dynamics scheme (154) was coupled to the regional climate model RCA4 developed at SMHI. This new model could be run at a much higher resolution than global climate models and the idea was to see if a more detailed description of aerosols at higher horizontal resolution could improve the simulation of cloud properties and the resulting impacts on the radiation balance. Model simulations over Europe and an eight-year period showed improved spatial, seasonal, and vertical distribution of cloud droplet number concentrations, cloud droplet radii and cloud liquid water compared to the original stand-alone RCA4 model. This resulted in a significant decrease in the total annual mean net radiation fluxes at the top of the atmosphere by \(-5 \text{ W m}^{-2}\) over the European domain (137).

Within SCAC, Stockholm University supported the development of an updated aerosol-cloud microphysics module in NorESM version 2 (155). This module includes, among other things, resolved heterogeneous ice nucleation initiated by dust and soot aerosols. In an unpublished study, NorESM version 1 was also evaluated against different aerosol and cloud measurements in the Arctic. The evaluation showed that the model overestimates aerosol transport to the
Arctic (mainly occurring at altitudes higher than ~1 km) while it underestimates aerosol size at the surface within the Arctic.

For the AMAP 2021 assessment SMHI, within SCAC, led an evaluation of observed and simulated cloud properties in the Arctic using satellite observations. Eight models participated, including NorESM and MATCH-SALSA-RCA4. The model evaluation revealed large differences between observations and models. Different satellite datasets also have a large spread among themselves. This is therefore an area where further work in both measurements, satellite-based observations and modelling will be required to narrow the range of uncertainties in cloud properties.
5.6. Integrating the economic and the environmental systems

- Established and improved Swedish competence in integrated assessment modelling,
- Collected data on new types of control measures, their costs, and effects,
- Highlighted the importance of integrating climate policies with air pollution policies,

5.6.1 Establishing national competence in systems analysis and decision support models

Whilst air pollution policy was early to recognize the multi-pollutant, multi-effect nature of air pollutants related to acidification, eutrophication, and ground-level ozone, the scientific advances made over the last 30 years has expanded the need for an integrated systems approach to air pollution control. The improved understanding over the last 20-25 years have added human health, climate change, and the marine environment to the list of problems attributable to excessive emissions of air pollutants. And through the formalization of the impact pathway approach (156, 157) in the EU research project ExternE, the link between the environmental and the economic systems could be represented in a structured manner. Starting from around 2000, air pollution policy support tools could systematically quantify both costs and benefits to human welfare from air pollution policy proposals. But even though the framework was established 20 years ago, there are still ongoing needs for improvements in data as well as in methods.

In the Swedish air pollution research presented here, the systematic integration of the economic and environmental systems started with a feasibility study on integrated assessment modelling research from a Swedish perspective (158). Starting with the first phase of SCARP, IVL led a research group in the efforts to use and establish a national understanding of the details of the IIASA IAM model Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) (159-161). The GAINS model is developed to support policy by identifying the most cost-effective use of emission control measures in order to reach specified air quality goals such as reduced acidification or improved human health. The model has since the negotiations leading to the Air Convention 2nd Sulphur protocol been an important decision support tool for air pollution policymakers in the Air Convention and the EU.

During the second phase of SCARP, IVL also led the work to establish national competence in air pollution control benefit assessments using the Alpha-Riskpoll (ARP) model developed by Ecometrics Research and Consulting (EMRC) (162-164). The ARP model allows for economic impact assessment of air quality in 38 European countries. It is based on estimates of current and future populations, specification of the relationship between poor air quality and poor health conditions for seven different health endpoints, as well as monetarised estimates of the welfare costs of these outcomes. The GAINS and ARP models together can identify socio-economically efficient levels of air pollution emission control.

Starting with SCAC, the Swedish research expanded its focus from mainly using the models for scenario analysis into also developing the model code and input data to improve the models. As an example, one analysis studied how the economic perspective that is used during identification of effective measures affects the cost-effective combination of technologies for
society (165). The variation of economic perspectives was represented by different values on interest rates and lifetime of investment in the measures, representing a corporate or a social planner perspective). Although results were irregular,

Figure 5 shows for the Nordic case that for certain air quality policy ambition levels, the economic perspective has substantial effect on in which sectors emission control would be perceived as cost effective. This in turn can affect the socio-economic costs of emission control (Figure 5a) and in which sector emission investments in emission reductions are deemed cost-effective (Figure 5b).

![Image](image-url)

*Figure 5: a) Social Planner air pollution emission control cost curves for two cases when identification of effective measures is originally calculated either with a social planner perspective on the economy (blue line), or with a corporate perspective (red line). b) the perspective-induced difference in social planner emission control costs per sector for an 85% policy ambition level for Denmark, Finland, Norway, and Sweden.*

5.6.2 Increasing the number of abatement measures & monetized benefits considered in models

One aspect that always needs updates or improvement in models is the accuracy and validity of the data included. For the GAINS model, this is includes the data on emission control measures and their costs. With finance from SCARP and additional funding, it was possible to gather data on costs and effects of energy efficiency improvements in the European household sector (166). These data served as input during the presentation of the GAINS model version ‘GHG mitigation calculator’ at the UNFCCC COP14 in Poznan, Poland (167). Later, and based on earlier Swedish and EU research (168, 169), research in SCAC produced estimates on emission control costs and effects from measures taken to control emissions from shipping (162). These cost estimates have been later used by IIASA for an EU impact assessment of introducing emission control areas in the Mediterranean Sea (170).

There are a couple of data collections that are yet to be fully implemented in decision support models, but where research in SCAC has contributed to the development. To these belong the complex issue of non-technical measures, that most often involves behavioural changes (171,
The research group is also preparing a manuscript detailing welfare costs of three hitherto ignored health outcomes attributable to air pollution: myocardial infarction, stroke and preterm birth (Figure 6, (173)). The results from this research has already been used as input to the CBA supporting the EU Second Clean Air Outlook (6).

Figure 6: Swedish socio-economic damage costs of one incidence of stroke, myocardial infarction or preterm birth induced by air pollution

5.6.3 Integrated analysis of air pollution & climate change policies

Just as air quality and climate change interact on a physical level in the atmosphere, so do the policies implemented to reduce the problems. In this case, however, the interactions rather relate to economics and policy target achievements. In general, the implementation of a climate policy will reduce the subsequent costs of implementing an air pollution policy, but an integrated approach can reduce costs even more. However, the size of the cost reduction is sensitive to the policy instrument chosen to implement a climate policy. If emission reductions rather than cost savings are prioritised, it is easy to find beneficial interactions between climate and air pollution policies. However, if control cost interactions are to be included, the size of the potential benefits of policy interaction is sensitive to the instruments used in the respective policies. Also in this field, Swedish research in SCARP, CLEO and SCAC has helped improve our understanding of how and under what circumstances co-benefits can be ensured and trade-offs avoided.

As an example from SCARP, Apsimon, Amann, et al. (174) highlighted that when analysing costs for society, a general rule-of-thumb is that climate policies are co-beneficial for air pollution control costs, but that the size of the co-benefit is largely dependent on the climate policy chosen and how ambitious its GHG targets are. Nordic research has also helped highlight that the type of policy instrument used is important. For example, GHG emissions trading can to some extent reduce European co-benefits between GHG and air pollution control (175), and SCARP research showed that GHG-strategies dependent on a large increase in biofuel use are at risk of inducing negative health effects as well as impeding climate benefits due to SLCF emissions (176). Typical examples of trade-offs include the shift from fossil to biofuel which is supposed to decrease CO₂ emissions but at the same time risks increasing the emissions of air pollutants. Conversely, SCAC research helped separate the effect of air pollution policies from...
other emission driving changes such as transitions of the energy system, industrial change, and climate policies. Through utilisation of decomposition analysis based on Swedish official emission data it was shown that Swedish direct efforts to reduce SO\textsubscript{2} emissions was responsible for at least 26-27% of the observed SO\textsubscript{2} emission reduction 1990-2012 (177).

A final and somewhat unexpected result from SCAC relates to the effect that climate metrics have on cost-effective SCLF emission control. The representation of SLCF climate effects is almost always done via the use of climate metrics, single number values deflating a complex climate dynamic into a direct climate exchange rate with CO\textsubscript{2} emissions. The conversion to a CO\textsubscript{2}-related metric is controversial and will obtain numerical values that can vary quite a lot. For soot the value range is between 120-1480 kg CO\textsubscript{2} per kg soot for the common metrics GWP\textsubscript{20} and GWP\textsubscript{100}, and even larger if considering a reasonable uncertainty range (4.6 – 2240). For NMVOC the range appears smaller (0.8 – 18). But research in SCAC showed that the choice of which climate metric to use don’t have much effect on which SLCF emission control measure that can be considered cost effective. Despite the large variance in metric values, the ranking of control measure with respect to cost-effectiveness will almost always give the same order, regardless of whether the measure controls emissions of soot, CH\textsubscript{4} or NMVOC (Figure 7, (178)).

Figure 7: The cost effective rank of 10 options (symbols at the bottom) to reduce air pollution with significant climate effect as a function of which climate metric that is used (GWP or GTP with 20 or 100 year horizons for European or global average emissions). Explanation of abbreviations: Mod. boiler = investment in newer residential sector boilers, Man. ferm. = manure fermentation in the agricultural sector, Pellets = use of pellets in residential sector boilers, SL-cover = covering of liquid slurry tanks in the agricultural sector, 4S S-mob = use of 4-stroke snow mobiles, 4S & El NRMM = use of 4-stroke engines and electric engines in smaller non-road mobile machines, SL. acid = slurry acidification in the agricultural sector, W. solv = use of water-based solvents in products, Mod.NRMM = investment in newer non-road mobile machines.

The exception to the main result, that the choice of climate metric is almost irrelevant for the identification of cost-effective emission control measures, is NO\textsubscript{x} emission control (due to
inverse short- and long-term climate impact of NO\textsubscript{x}). As a word of caution, it is always important to remember that the SLCF conclusion above is not applicable to choices between CO\textsubscript{2} and SLCF emission control.

5.6.4 Air quality, shipping and the marine environment

Over the last 10 years, Swedish research on costs and effects of reducing emissions from shipping have provided decision support models with data and method developments useful for international environmental policies. The economic research is, however, currently undergoing an interesting expansion, partly originating from SCAC results (162). In addition to shipping emissions’ well-established negative welfare effects via contribution to climate change and air pollution, research now also integrates effects on the marine environment through toxic wastewater effluents and emissions of engine exhaust to air causing marine eutrophication. Surprisingly, for the sensitive Baltic Sea, the deposition of nitrogen from Baltic Sea shipping induces welfare costs for the surrounding countries that are of the same magnitude as the welfare costs of the health effects caused by the emissions to air Figure 8, (179). This new system expansion into the marine environment is a first attempt to widen the system perspective on welfare effects of air pollution control into the marine environment.

Figure 8: 2018 damage costs (mean values) caused by shipping in the Baltic Sea divided into the impact categories marine ecotoxicity, marine eutrophication, reduced air quality and climate change (179).
5.7. Development of tools

- Improved physical process descriptions, and increased geographical and temporal resolution in a CTM and dispersion model,
- Contributed to valuable model intercomparison studies
- Established Swedish modelling competences with Earth System Models and Integrated Assessment Models

5.7.1 Atmospheric chemistry transport and air pollution dispersion modelling

Accurate source-receptor modelling of air pollution is crucial for the development of cost-effective control strategies and for the assessment of the outcome of air pollution control, including trend analyses. It is also of crucial importance for our understanding of mechanisms and processes. The development of atmospheric modelling over the last 20 years has in an unprecedented way increased our ability to understand and describe how different factors are influencing transport and chemistry of pollutants from global to street levels. The recently developed tools and instruments have already proven their suitability for policies and have been used for setting control priorities and analysing outcomes and trends in more reliable ways than before.

A number of specific developments have been facilitated partly or completely with the aid of the research programmes. Over time computational power in supercomputers has increased, improving the possibility for higher model resolution, simulating longer time periods and adding more complexity to models. Many long-term modelling efforts have been completed in the research programmes, which has only been possible with access to high-performance supercomputers. Before the year 2000 it was considered a large effort to simulate one or a couple of years of ozone forming photochemistry, while within CLEO, datasets were produced describing ozone exposure and nitrogen deposition for hundreds of years including multiple climate scenarios at 50 km resolution. Even with the performance of the computational systems at that time, this effort is unprecedented, and no other modelling team has, to our knowledge, so far managed to repeat this effort.

Today, the CTMs approach higher and higher resolution, and covering Europe at 10 km resolution is not uncommon. For smaller areas (such as Sweden or the Scandes mountains) 3-5 km is possible even for longer time periods (36). In urban areas, exposure modelling can be done with approximately 20-50 m resolution (40, 48). Recently, a new generation of downscaling methods have been developed facilitating air pollution exposure estimates at this high resolution for long time periods for the whole of Sweden (180). Future work involves assimilation of measurements at different spatial scales, further improvements of emission inventories, quantitative evaluation against measurements and improved parameterizations of the involved dispersion models. Today’s CTM studies of future scenarios of air pollution are out of date and in dire need of updates with respect to climate scenarios, air pollution emission scenarios, physical processes, inclusion of particles and resolution of the calculated exposure to both ecosystems and health.
Aerosols are difficult to describe correctly in models due to the complexity in chemistry, differences in size and processes involved in their ambient transformations, diversity of emissions sources and the complexity and variety of measurement techniques involved in model evaluation. Throughout the research programmes, efforts have been made to improve the description of particle mass, its chemical constituents and particle number size distribution. These efforts include aerosol dynamics and secondary organic aerosol formation – time consuming calculations for which it has been beneficial to have access to supercomputers. Currently, a number of difficulties remain. Two major remaining issues spanning the spatial scales are improved emission inventories for residential wood combustion (in Europe as well as nationally in Sweden), and improved knowledge on condensable organics: both emissions and atmospheric chemical and physical transformation.

Below is a list of the major developments that have been conducted in the CTM MATCH throughout the research programmes:

- Aerosol dynamics was introduced in the SCARP programmes creating the CTM MATCH-SALSA (154, 181),
- Building on this development, formulation of cloud condensation nuclei was introduced (137),
- Secondary organic aerosol formation (a number of volatility-based schemes exist in the model, as well as simplified descriptions) (37, 182-184),
- Biogenic emissions of VOCs (37, 182-184), and
- The measurement-model fusion approach to estimate air pollutant concentrations and deposition (36, 39).

Describing exposure to air pollution at local scale over long time-periods is demanding in terms of input data requirements and requires a chain of tools, from regional through urban to local, and methods that capture the relevant processes at the different scales involved. The research programmes funded by the Swedish EPA have been critical in building capacity to allow the type of exposure modelling currently applied. Continuity in research over several years and collaboration with authorities and institutions from the Swedish air quality community involved has been essential in making this possible.

5.7.2 Climate modelling

In SCAC SMHI developed the new model system MATCH-SALSA-RCA4 (137). This is an off-line coupled system, where the MATCH-SALSA CTM (154) is coupled to the Rossby Center regional climate model, RCA4. The coupling is done by first forcing RCA4 with reanalysis meteorological data and sea surface temperature and using the standard cloud droplet number concentration formulation in RCA4. The meteorology from this simulation is then used to drive MATCH-SALSA. Cloud droplet number fields obtained from MATCH–SALSA are then fed back into a new RCA4 simulation which for example can be compared to observations. Modifications in radiative forcing induced by changes in air pollution emissions affecting the aerosol concentrations, size distribution, and chemical composition can also be studied.
5.7.2 Model intercomparison

Validation of models in relation to observations as well as to the performance of other models is a crucial process for building of trust and legitimacy. A community of modellers in Europe has been formed over the last decade with the aim to increase the overall expertise and confidence in model outputs. The funding from the research programmes has facilitated participation in model intercomparison studies, for example the EuroDelta-Trends (ED-trends) initiative (37), under TFMM within the Air Convention. Participation in the AMAP and POLMIP model intercomparison efforts has also been enabled by funding from the research programmes. Participation in such efforts is positive for multiple reasons:

- It allows for international networking and provides a way to search for future joint research projects, as presented in Chapter 3.6.
- It allows for coordinated tests of multiple models. This results in quality assurance of operational systems as well as of the models used for exposure assessments, source attribution, future scenario studies, forecasting and input to epidemiological and ecological studies. As one example, multiple operational models in CAMS were tested in the ED-trends initiative. This cooperation may result in the identification of development needs and exchange of model code, parameterisations and/or data sets that can be used to improve models or model estimates in other projects including the national research programmes.
- The modelling efforts produce so called ensemble estimates. It has been shown that ensembles typically perform better than individual models and the spread in model outputs gives an indication of uncertainty and robustness. The long-term data sets calculated by six models in the ED-trends initiative has been used for impact assessments (e.g. (185, 186).
- In these international collaborations, the research teams distribute the work to evaluate and analyse the results, including trend assessments and sensitivity analyses, usually reaching further than any single research team can. The ED-trends has resulted in:
  - 6 scientific papers (37, 38, 44, 183, 184, 187),
  - a large dataset publicly available,
  - a number of international assessment reports (185, 186).
- The work on model evaluation in the Arctic has so far resulted in:
  - 5 scientific papers (151-153, 188, 189),
  - contributions to two AMAP assessment reports on SLCF (148, 150).

It is extremely difficult to raise funds for such an effort through international funding agencies such as the EU. The contributions of the research programmes have been vital for Swedish researchers to contribute to these efforts.

5.7.3 Integrated Assessment Modelling with GAINS

Although not a mandatory part of the national reporting to the Air Convention, input from integrated assessment modelling is fundamental when negotiating ambition levels for international air quality agreements. As all models, integrated assessment models are opaque for laymen, a feature that can reduce trust in model results. The importance of integrated assessment modelling for air pollution policy was recognised early by Swedish civil servants. In 2006 a feasibility study was made in the ASTA programme (158), and the call for research that was the basis for SCARP requested the establishment of Swedish integrated assessment
modelling competence, especially competence in GAINS modelling. As noted earlier, in the first years the focus was on learning basic functionality and how to use the model, how to set up and analyse scenarios, how to adjust web interface functionality, and on compiling data on emission control measures. In 2016 the Swedish GAINS model activities started to focus on model script development. Since 2016, a Fennoscandian version of the GAINS model cost-optimization had been developed. In its current version, the Scandinavian GAINS model allows for identification of cost-minimal strategies to reach both air quality and SLCF targets. It also allows for sensitivity analysis of emission control costs (165), and for identification of cost-optimal combinations of emission reductions at sea and on land. GAINS Scandinavia can also identify how high the external cost of CO2-emissions would have to be to provide economic motivation for changing air pollution control strategies (190).

5.7.4 Benefit assessments with the ARP model

GAINS modelling has been very important since it identifies how European countries can reach several air pollution targets simultaneously at the lowest cost. But since 2005, analysis of benefits in addition to costs has become more and more important in Europe. Within EU and the Air Convention, the Alpha-Riskpoll (ARP) model is the most prominent tool, and in the SCAC programme researchers started using the ARP model for cost-benefit analysis of shipping emission control (162). ARP contains information on a wide range of human health effects attributable to air pollution, the magnitude of the response and the benefits for society of reducing the occurrence of these health effects. Swedish research is also aiding to the further development of the ARP model. And as presented earlier, benefit estimates of reduced occurrence of stroke, myocardial infarction and preterm birth will be submitted for publication during 2021.
6. KEY SCIENCE – POLICY ACHIEVEMENTS

The Swedish research programmes presented here have co-existed with an ongoing policy work to achieve the Swedish National Environmental Quality Objectives and to support an active international air pollution policy agenda (Figure 9). Within the international policy process, environmental issues often take many years to go from problem-recognition to solution. Therefore continuous, and long-term research, as well as expert knowledge are instrumental to ensure that environmental problems are solved, or at least reduced. Given the applied nature of the research programmes and the active interaction and communication between researchers and policymakers, the research programmes have provided input to several air pollution policy processes, through meetings, conferences, bilateral discussions. Often also through day-to-day informal communication via emails, telephone calls etc.

Figure 9: Science – policy timeline 1999 -2020. The duration of selected research projects and development periods of national and international air pollution policies. Light yellow box colour indicates Air Convention activities and green boxes indicate EU activities

6.1. A close interaction between national and international science and policy
Several of the scientists within the programmes have been deeply involved in various policy processes, both nationally and internationally. Some have had continuous roles; others have been involved on project- or intermittent basis. Internationally, the focus has been on the Air Convention and scientists from the programmes have been and are still deeply involved in many of the subsidiary groups, including the co-organised Air Convention/WHO Task Force on Health (Figure 10). The Swedish programmes have ensured scientific credibility of the Swedish participants in these international bodies and expert group meetings, and it has often been the case that Swedish researchers have taken leading roles in the working bodies. Researchers in the programme have also been involved in related contract work for the European Commission (e.g. 168, 191).
Figure 10: Experts from the research programmes that have been involved in the Air Convention's activities.
Other policy venues with involvement from Swedish air quality researchers are the WHO, WMO, the European Commission, AMAP and CCAC. The outcomes of the involvement of these researchers, in addition to participation in official meetings and workshops, have often been co-authorship in policy-supporting reports (Table 2).

Some science policy activities have had a large influence for policy, e.g., the participation of programme scientists, in particular from IVL, in bilateral IAM capacity building in EECCA countries and south-eastern Europe (Russia, Belarus, Ukraine, Serbia), thereby reducing the information gap between Western European countries and Eastern European countries during the Air Convention negotiations. As an example, IVL and IIASA hosted a first GAINS model training session for EECCA country experts in February 2009 (with financial support from the Swedish EPA and the Swedish International Development Agency. This session was followed by several follow-up sessions with local experts in Russia, Belarus, and Serbia. The Serbian case is most recent (2018-2020) and of particular interest. Knowledge in GAINS modelling, and ability to produce analysis with the GAINS model, is instrumental to achieve an equal basis in the air quality-related accession negotiations between official representatives from Serbia and the EU. Here Swedish GAINS model training has been much appreciated. As late as December 2020, new knowledge-sharing efforts with Bosnian researchers and air quality managers have been initiated. And there are discussions to initiate GAINS-related activities in Croatia during autumn 2021.

**SUPPORTING FACT-BASED INTERNATIONAL ENVIRONMENTAL POLICY**

**Contribution to 8 policy-supporting assessment reports**

* The 2004 EMEP assessment of historical monitoring data,
* The 2004 assessment and model intercomparison of the EMEP CTM,
* The 2004 RAINS model review
* Clearing the Air – 25 Years of the Convention on Long Range Transboundary Air Pollution (2004),
* The European Nitrogen Assessment (2011)
* AMAP Assessment: Black carbon and ozone as Arctic climate forcers (2015),
* Towards Cleaner Air, UNECE Scientific Assessment (2016),
* AMAP Assessment: Impacts of short-lived climate forcers on Arctic climate, air quality, and human health (2021)
Table 2: Involvement of scientists from the research programmes in international policy-directed bodies and processes, together with contributions to published key assessment reports.

<table>
<thead>
<tr>
<th>Name</th>
<th>Organisation the scientist has taken part in</th>
<th>Contributions to reports of policy relevance</th>
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<tbody>
<tr>
<td>Peringe Grennfelt</td>
<td>Chair WGE, 2011-16 Member EMEP SB and its Bureau 1999-2016</td>
<td>1) The European Nitrogen Assessment (11)&lt;br&gt;2) Towards Cleaner Air (17)</td>
</tr>
<tr>
<td>Per-Erik Karlsson</td>
<td>Member of ICP Vegetation</td>
<td></td>
</tr>
<tr>
<td>Joakim Langner</td>
<td>Expert in CCAC, AMAP, TFMM, TFHTAP.</td>
<td>AMAP black carbon and ozone assessment 2015 (148)</td>
</tr>
<tr>
<td>Filip Moldan</td>
<td>Chair of Joint Expert Group on Dynamic Modelling. Member of ICP M&amp;M</td>
<td>Towards Cleaner Air (17)</td>
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<tr>
<td>John Munthe</td>
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<td>Towards Cleaner Air (17)</td>
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<tr>
<td>Håkan Pleijel</td>
<td>Member of ICP Vegetation and TF M&amp;M</td>
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<tr>
<td>Stefan Åström</td>
<td>Co-chair of Task Force on Integrated Assessment Modelling</td>
<td>Towards Cleaner Air (17)</td>
</tr>
</tbody>
</table>

Of less informal nature but still relevant is the active engagement of Swedish EPA experts in programme meetings and discussions, which has been particularly important. Experts from the Swedish EPA have been invited to internal programme meetings, and those involved in policy development and responsible for NEQO progress reporting have generally participated. Their participation has simplified knowledge transfer between science and policy, and through the informal contacts, they have received information on early results and got an understanding of relevance and uncertainties in the results. In addition, programme participants have quite frequently been contacted by experts from Swedish EPA and other administrations regarding the underlying science for various issues with respect to air pollution policies.

⁹ https://community.wmo.int/governance/commission-membership/research-board/ssc-epac/mmf-gtad-sc
6.2. Other workshops and initiatives

In addition to the Saltsjöbaden workshops presented in Chapter 4, other workshops have been organised directly by, or in close connection with, the research programmes (Table 3). These workshops have been significant means for paving the road for further development of science-based policies. Especially the ASTA programme offered unique options to take initiatives in addition to the above mentioned Saltsjöbaden workshops. Here, a few initiatives are listed, most of them organised during the ASTA period.

Establishing the Joint Expert Group on Dynamic Modelling

The critical loads concept, so successfully used in the negotiations for the Gothenburg protocol, is based on stationary conditions and does not consider the time factor. To assess outcomes of emission abatement measures, there is also a need to know how long it will take to achieve a certain status of ecosystems. This issue was the basis for research and discussions during the 1990s and in connection with a critical loads workshop in Copenhagen in 1999, the idea came up\(^\text{10}\) of establishing a forum for an activity for developing and considering the dynamics in air pollution effects. A workshop was organised under the ASTA umbrella involving those who were looking into the problem. After a first workshop in 2000, it was realized that there was a need to meet regularly and the group of mainly modellers have met almost annually since then. ASTA supported a series of the early workshops.


Towards the end of the 1990s it became evident that the concentration-based exposure indices used in the policy work of the Air Convention, mostly AOT40, didn’t accurately represent the influence of environmental factors that control ozone uptake and, in the end, effects. An initiative was taken by ASTA researchers to organize a workshop for the development of ozone exposure indices based on the actual uptake of ozone by the plants. The workshop was held at Hindås outside Gothenburg 19-22 November 2002. It attracted a large number of participants from many European countries. At the workshop, response relationships for crops and forests were presented and discussed. The main conclusion from the workshop was that critical levels and response functions, based on stomatal ozone uptake - response relationships, was recommended for use for agricultural crops within the Mapping Manual of the Air Convention. Regarding forest exposure, it was concluded the ozone dose based on stomatal uptake of ozone represented the most appropriate approach to setting future ozone critical levels for forests trees (194). The workshop also resulted in a special issue of the scientific journal Atmospheric Environment. At subsequent meetings in Obergurgl in Austria (2005) and Ispra in Italy (2009) the discussion and development continued. At the Ispra meeting, the concept of POD was coined to denote the stomatal uptake of ozone by plants, which is considered to represent the physiologically relevant dose. It should be emphasized that the annual ICP Vegetation Task Force Meetings of the Air Convention also were instrumental in the continued development of response relationships. Finally, in 2017, the current POD-based methods to estimate effects of ground-level ozone were adopted and included in the Mapping Manual of the Convention. The

\(^{10}\) The idea was put forward by Alan Jenkin (United Kingdom) and Filip Moldan (Sweden).
important contributions by the Swedish researchers to this work were supported by the CLEO and SCAC programmes.

**PM workshop, Stockholm 20-21 October 2003**

As part of the development of the CAFE strategy, a stakeholder workshop was organised in connection with the preparation of the so called Second Particulate Matter Position Paper in Stockholm 20-21 October 2003. The workshop was attended by participants from a wide range of interests. Data from several scientific studies were presented with various examples of experiences in cities (Berlin, Stockholm, Madrid, Milan, London and Duisburg). The major focus of the presentations was on traffic-related sources and their relations to influence from long range transport (e.g. Berlin, London and Stockholm). Wood burning (Stockholm) was recognised as a major source as well (195).

**Workshop on Base Cations, Gothenburg November 2003**

Emissions and deposition of base cations are of importance as a neutralising factor in relation to acid deposition, particularly for the long-term acidification effects in ecosystems. Due to the lack of reliable emission data, a workshop was organised under the ASTA umbrella in 26-28 November 2003 in Gothenburg in collaboration with EMEP and WGE under the Air Convention. At the workshop methodologies for emission inventories as well as deposition measurements and modelling approaches were discussed. Experiences from several countries were presented, and the workshop led to a more uniform approach to the issue and to the development of more consistent deposition maps (196).

**Supporting fact-based information to all stakeholders**

<table>
<thead>
<tr>
<th>10 national stakeholder institutions actively got regular input from the research programmes</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Swedish Ministry of Environment</td>
</tr>
<tr>
<td>The Swedish Environmental Protection Agency</td>
</tr>
<tr>
<td>The Swedish Environmental Protection Board</td>
</tr>
<tr>
<td>The National Board of Forestry</td>
</tr>
<tr>
<td>The Swedish Energy Agency</td>
</tr>
<tr>
<td>The Swedish Transport Administration</td>
</tr>
<tr>
<td>Swedish Countys and municipalities</td>
</tr>
<tr>
<td>Elforsk</td>
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<tr>
<td>BIL Sweden</td>
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<tr>
<td>Airclim</td>
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</tbody>
</table>

**Social science for international air pollution policies, Gothenburg 5-7 October 2005**

Social science examining the scientific background and processes leading to international agreements has seldom been part of air pollution research programmes. In ASTA, an initiative was taken to involve social scientists with the aim to study the dialogue between various stakeholders with particular emphasis on the relations between scientists and policymakers. To get an overview of the international science in the field and to obtain a wider perspective on the issue an international workshop was organised in Gothenburg. The workshop formed the starting point for a monograph on the issue (197).
Workshop on the importance of non-technical measures, Gothenburg 7-8 December 2005

Air pollution control strategies to reduce transboundary air pollution within the Air Convention and EU are mainly built upon information on emission-reducing technologies that can be implemented. But other types of measures, often informally grouped as ‘non-technical measures’, are recognised as necessary to reach air quality targets and ensure co-benefits with climate change. In December 2005, the ASTA programme and the Nordic Council of Ministers organised a workshop on the importance of non-technical measures for air pollution control and the possibility to integrate these into integrated assessment modelling (158).

50 years of acid rain science and policy – Symposium, Stockholm November 2017

In October 1967, the first public alarm on an ongoing acidification of precipitation, lakes and streams was published (198). To manifest the early observations and the successful outcome on air pollution control, a symposium was organised in Stockholm 6-7 November 2017. The symposium was supported by the Swedish EPA, the Norwegian government, the Nordic Council of Ministers and others (14, 199). More than 70 scientists and policymakers met to analyse and discuss processes and outcomes as well as how the experience could be used to address future environmental challenges. Several scientists from the Swedish research programmes attended and contributed to the outcome of the symposium.

Stefan Åström giving a presentation on black carbon and the Arctic during a side event of the 40th anniversary of the UNECE Air Convention.
Table 3: Workshops and other meetings under or in close connection with the five research programmes.

<table>
<thead>
<tr>
<th>Workshop</th>
<th>Data</th>
<th>Research programmes and other org. involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Saltsjöbaden workshop at Saltsjöbaden</td>
<td>10-12 April 2000</td>
<td>ASTA in collaboration with NCM and the Air Convention</td>
</tr>
<tr>
<td>Establishment and technical and financial support to the Joint Expert Group on Dynamic Modelling under the Air Convention</td>
<td>Annual meetings from 2000</td>
<td>ASTA, SCARP, SCAC and the Air Convention</td>
</tr>
<tr>
<td>1st International Workshop on Validation and Evaluation of Air Emission Inventories, Gothenburg</td>
<td>14-16 October 2002</td>
<td>ASTA together with the Air Convention</td>
</tr>
<tr>
<td>Establishing Ozone Critical Levels II, Gothenburg</td>
<td>19-22 November 2002</td>
<td>ASTA, NCM</td>
</tr>
<tr>
<td>Emissions, transport, deposition and effects of base cations in relation to acidification, Gothenburg</td>
<td>November 2003</td>
<td>ASTA, NCM</td>
</tr>
<tr>
<td>Saltsjöbaden II, Gothenburg</td>
<td>5-7 October 2004</td>
<td>ASTA, EC, NCM, the Air Convention</td>
</tr>
<tr>
<td>Social science for international air pollution policies, Gothenburg</td>
<td>5-7 October 2005</td>
<td>ASTA, NCM</td>
</tr>
<tr>
<td>Workshop on non-technical measures in integrated assessment models, Gothenburg</td>
<td>7-9 December 2005</td>
<td>ASTA, NCM, the Air Convention</td>
</tr>
<tr>
<td>SNAP – Final conference</td>
<td>June 2006</td>
<td>SNAP</td>
</tr>
<tr>
<td>Nitrogen critical loads for terrestrial ecosystems in low deposition areas, Stockholm</td>
<td>29–30 March 2007</td>
<td>ASTA/SCARP, the Air Convention</td>
</tr>
<tr>
<td>Saltsjöbaden III, Gothenburg</td>
<td>12-14 March 2007</td>
<td>SCARP</td>
</tr>
<tr>
<td>Assessment of air pollution for epidemiological studies, Stockholm</td>
<td>6-7 November 2007</td>
<td>SCARP</td>
</tr>
<tr>
<td>Air pollution for climate change – Collaboration for the best results (in Swedish), Stockholm</td>
<td>12-13 November 2008</td>
<td>SCARP</td>
</tr>
<tr>
<td>SCARP - final conference, Stockholm</td>
<td>12-13 March 2013</td>
<td>SCARP</td>
</tr>
<tr>
<td>Saltsjöbaden V, Gothenburg</td>
<td>24-26 June 2013</td>
<td>SCAC, Swedish EPA, NCM, the Air Convention</td>
</tr>
<tr>
<td>Forest management in a changed climate, Stockholm</td>
<td>16 October 2013</td>
<td>CLEO together with KSLA</td>
</tr>
<tr>
<td>Seminar on Low Emission Zones – how to estimate the air quality benefits, Stockholm</td>
<td>17-18 June</td>
<td>SCAC together with EU project(s)</td>
</tr>
<tr>
<td>Ground-level ozone – present-day and future risks for impacts on vegetation</td>
<td>9 March 2015</td>
<td>CLEO</td>
</tr>
<tr>
<td>How to put SLCP policies into practice 17th of April, Norrköping</td>
<td>17 April 2015</td>
<td>SCAC</td>
</tr>
<tr>
<td>Saltsjöbaden VI, Gothenburg</td>
<td>19-21 March 2018</td>
<td>SCAC, Swedish EPA, NCM, the Air Convention</td>
</tr>
<tr>
<td>SCAC Final conference.</td>
<td>19 May 2020</td>
<td>SCAC</td>
</tr>
<tr>
<td>The first Nordic five-city on-line conference on air quality, AQ4ALL - Air Quality for All</td>
<td>10-11 June 2020</td>
<td>SCAC, Nordic Welfair, EUA-BCA</td>
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</table>
7. FUTURE CHALLENGES

International air pollution issues of importance for Swedish policies were until around 2010 dominated by activities and decisions at the Air Convention and the European Union. Other organisations also had some importance, e.g. the Nordic Council of Ministers, the Arctic Council, and its expert body AMAP. However, over the last 10 years new actors and processes have more clearly entered the scene. Some of them have a clear agenda on air pollution while for others air pollution is part of a wider scope. These new actors include CCAC, UN Environment, and WHO. It is also worth mentioning that some global institutions and conventions include air pollution issues. The World Bank, the Organisation for Economic Co-operation and Development, as well as regional development banks are examples of institutions. The UNFCCC, the UN Convention on Biological Diversity, and the UN Sustainable Development Agenda for 2030 all include issues that are relevant for air pollution.

It is expected that these new actors, Conventions, and processes may play an increasing role for air pollution control, especially on the global scale. Even if their main aims don’t include science, they have scientific interests, and their agendas will to a large extent rely on scientific evidence and findings. Air pollution research will therefore in the future be of utmost importance, but the increasing number of actors and processes will probably also add requests for a wider interaction between the scientific and policy communities.

In addition to policy-oriented actors and processes, there are initiatives and processes aiming for scientific collaboration and support on air pollution in a wider international sense. This support includes scientific research as well as data collection and dissemination. On the European scale, EU-supported research is here the most important when it comes to future research projects and programmes. For data collection, the Air Convention and EEA play a central role on the European scale, and to some extent even on the global scale. Future research needs must therefore consider the already well-established research infrastructure in Europe, demonstrated by interdisciplinary exchange and pooling of research data within Air Convention bodies, e.g., CCC, CCE, MSC-West, TFTEI, and CIAM. On the global scale WHO is of outmost importance, and it organizes several activities with relevance for air pollution research, also UNEP is engaging more and more in air quality issues.

The SDG approach is requesting that air pollution is considered with a system perspective. This implies that when analysing and assessing air pollution, it is necessary to consider the underlying mechanisms that cause the pollution, and how these mechanisms are integrated with biodiversity, climate, water quality and availability, food production systems, human health, urban livelihood etc. A system approach does not have to be global. A regional scale or even a local scale orientation is often appropriate. The ammonia problem is an example where the local and regional scales may be appropriate for policy – and even used today. Another is atmospheric high-pressure cells in the summer, where several air pollution and other environmental problems are linked, and the consequences and solutions are difficult to foresee without a broad systems approach.
The close air quality science-policy interactions in the presented programmes have ensured that scientific progress is aligned with policy ambitions to reach the NEQOs in acceptable and cost-effective ways. The research helps clarify and guide policy strategies towards the most important source sectors, regions, and emission control measures. Further, as knowledge develops, the research promotes adherence to the Precautionary Principle.

The future challenges for research identified in this chapter follow these soft science-policy principles. Contemporary and earlier approaches to emission reductions, based much on technical end-of-pipe solutions, are still relevant. But if society should meet the requirements of sustainability, there is a need to approach the fundamental issues that make up basis for the SDGs. In addition, traditional technologies have in many cases reached their limits of performance. It may now be time to extend the scope and see air pollution as an integral component of the SDGs. A thematic approach is therefore required to arrive at the measures needed to reach air quality objectives in various societal sectors. Not the least is this important since several of the SDGs are interacting, and achievement of one might impede achievement of another.

The SDGs are chosen as a framework in the following discussion on future research challenges. In this way the report follows established interdependencies of air pollution policy and the 2030 agenda (200, 201). These SDGs are to varying degrees linked to some of the NEQOs (Table 4). Correspondingly, the SDGs and NEQOs addressed are:

**Table 4: Sustainable Development Goals (SDGs) and National Environmental Quality Objectives (NEQOs) framing the future challenges for Swedish air pollution research**

<table>
<thead>
<tr>
<th>Sustainable Development Goal</th>
<th>Related National Environmental Quality Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG Goal 2: Zero Hunger</td>
<td>Clean Air, Reduced Climate Impact, Zero Eutrophication, Only Natural Acidification</td>
</tr>
<tr>
<td>SDG Goal 3: Good Health and Well-Being for People</td>
<td>Clean Air</td>
</tr>
<tr>
<td>SDG Goal 7: Affordable and Clean Energy</td>
<td>Clean Air, Reduced Climate Impact, Zero Eutrophication, Only Natural Acidification</td>
</tr>
<tr>
<td>SDG Goal 11: Sustainable Cities and Communities</td>
<td>Clean Air, Reduced Climate Impact</td>
</tr>
<tr>
<td>SDG Goal 13: Climate Change</td>
<td>Reduced Climate Impact, Clean Air</td>
</tr>
<tr>
<td>SDG Goal 15 Life on Land</td>
<td>Zero Eutrophication</td>
</tr>
</tbody>
</table>

#### 7.1. Improving our understanding of the links between air pollution and food production (SDG Goal 2, NEQO Clean Air)

With a global population expected to grow from today’s 8 to almost 11 billion inhabitants by the end of the 21st century, food availability will continue to be an ongoing environmental challenge. Many factors affect food production, and some of these are closely linked to air pollution.

**7.1.1 Ground-level ozone effects on food production**

Ozone is known to significantly reduce growth and yield of crops, with wheat and soybean as prominent examples of globally important crops with high ozone sensitivity. In a world of growing population and high (in some parts even rising) ozone concentrations, this poses a

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11 https://unece.org/air-pollution-and-food-production
threat to food security. Not only yield magnitude is affected. For some crops, there are also effects on crop quality. For protein and some minerals, the unit area yield is reduced by ozone exposure resulting in a reduced productivity of nutrients. Our understanding of the relationships between future ozone scenarios and the sensitivity of the various crops (including new varieties) needs to be followed, continuously investigated, and expanded to cover more crop species.

7.1.2 Aerosol effects on precipitation
Due to their strong influence on the surface energy balance, changing emissions of aerosol particles (or their precursors) are known to drive precipitation changes more efficiently than greenhouse gases (202). Furthermore, the effects of future aerosol reductions are likely to be felt more strongly at regional rather than global scales due to their heterogeneous forcing distribution and strong influence on circulation patterns. For example, more than one billion people rely on the precipitation that the Asian summer monsoon brings for water and food security. There is evidence that anthropogenic aerosols influence the Asian summer monsoon, but more efforts are needed to reduce uncertainty in estimates of the size and sources of the influence.

7.1.3 Aerosol direct effects on food production
Agricultural crop production is dependent on sunlight, in particular the partitioning between diffuse and direct sunlight. Atmospheric aerosols are known to affect the amount of downwelling solar radiation, and changes in anthropogenic emissions may result in global “dimming” or “brightening”. Climate models struggle to reproduce past trends in surface downwelling solar radiation, in particular over China (203). Important first steps to improve climate models in this respect are to improve emission inventories and complete representations of aerosol types with the aim to make sure that nitrates and organic aerosols are properly included.

7.2. Expanding our perspectives on human health effects (SDG Goal 3, NEQO Clean Air)
While the associations between air pollution exposure and detrimental health effects are established and confirmed by a large number of studies, there are important research gaps that need to be filled to promote good health and well-being for all people. The following section presenting some areas which can be considered of particular importance from a Swedish policy perspective.

7.2.1 Integrating air pollution and climate change effects on human health
A consequence of climate change will be more frequent and intense heat waves, often involving wildfires in many areas of the world. Sweden will also be a place of such episodes. Heatwaves are associated with increased mortality and during the heatwave in Sweden in the summer 2018 the excess mortality was estimated to more than 600, maybe 750 lives. (204). The risk groups for heat waves are similar to those for air pollution, and it is important to investigate the interactions, in particular those between heat, ozone and smoke from wildfires.
Further, human-induced climate change may increase the occurrence of droughts, increase areas of deserts and drylands, and thereby also emissions of dust particles, which affect air pollution levels in many regions of the world. Currently, global climate models as well as hemispheric and regional chemistry transport models generally fail to reproduce important historical trends in dust emissions, such as the past decadal changes of dust over East Asia (205). Correspondingly, scenarios for future dust emissions are very uncertain. To ensure consideration of a potentially important source of health effects, it is necessary to improve the parameterisation and the entire impact pathway of dust emissions.

7.2.2 The effect of air pollution on transmissibility of viruses
Another potential interaction effect that recently has been highlighted is that air pollution may be contributing to severe effects of the coronavirus pandemic. Particles are known to affect underlying conditions such as chronic respiratory and cardiovascular diseases that increase severity and fatality rates in infections, and the respiratory immune response and mucosal permeability (206). Air pollution particles may also act as carriers for viruses and thus increase transmissibility of infections. This transmissibility issue is less studied in the Swedish low-exposure environment than in other regions with higher exposure levels. Experimental studies of possible mechanisms, and epidemiological studies of effects of air pollution on incidence as well as case-severity in low-exposure environment are needed. In addition to the ecological studies, cohort studies with individual data, are also needed, to reduce the risk of confounding by other risk factors.

7.2.3 Health effects from exposure to ground-level ozone
European health impact assessments on ozone from EEA and others are usually assuming the existence of ozone concentration threshold levels under which no damage to human health occurs. However, in Swedish epidemiological studies on acute effects on mortality, morbidity and pregnancy complications (such as preterm birth) there is a clear effect of ozone without noticeable concentration thresholds (99, 207, 208). The existence of ozone thresholds is thus questionable. With a threshold under question, and the observed adverse changes in ozone exposure, it is possible that current health impact assessment in low ozone-exposure environments such as Sweden underestimates human health effects of ozone. Further studies that can help establish the effect of ozone exposure on human health over a range of concentration levels are thus needed.

7.2.4 Air pollution effects on child health
Children are vulnerable to air pollution. Within SCAC, and in other studies, it is shown that exposure during the first year is particularly detrimental. Observed effects on the pulmonary system will persist at least up to the teenage years. As an example, in a recent and yet to be published study in Stockholm on infants born during the 2010s, negative effects on the pulmonary function were observed. Also, an increasing number of studies suggest that early air pollution exposure could increase neurodevelopmental disorders in children.

Studies suggest that pregnancy is the period in which exposure to environmental pollutants seems to be most impactful concerning the onset of autism spectrum disorders (ASD) in children. A Swedish study recently found associations between air pollution exposure during the prenatal period and the risk of developing ASD (209). A review of studies on air pollution
and ASD including 20 articles found a strong association between maternal exposure to air pollution (especially PM$_{2.5}$) during pregnancy or in the first years of the children’s life, and the risk of the ASD (210). Another Swedish study found that children and adolescents living in areas with higher air pollution concentrations were more likely to have a dispensed medication for a psychiatric disorder during follow-up (211). The effects from air pollution on child and adolescence health needs more attention in general. And for some health effects such as neurodevelopmental disorders, research has just started and need to catch up with other health effects such as adult mortality. **Future studies need to clarify possible mechanisms, links to specific pollutants, and if the effects remain into adulthood.**

7.2.5 Are all types of small particles in the air equally detrimental to human health?

While experimental studies have indicated that combustion-related particles are the component of air pollution that is most detrimental to human health, the epidemiological studies, the foundation for health impact assessments and policy, have mainly focused on mass-based measurements or modelling of all types of particles smaller than a certain aerodynamic diameter (most often 2.5 µm). Several publications by WHO have stated that there is still insufficient evidence to recommend different exposure-response functions for different sources or types of particles of the same size (193, 212, 213). Consequently, most analysis of health impacts related to air quality focus on particulate matter and the same linear exposure-response functions are usually assumed, regardless of particle source and independent of the type of exposure data available. The current WHO recommendation is based on a meta-study (214), heavily influenced by epidemiological studies based on differences in concentrations between different cities.

But concern has been raised about the use of the same exposure-response function both for regional background exposure and the contribution from local sources (133). There is also growing evidence that resolving within-city contrasts in exposure leads to several times higher effect estimates (47, 215, 216). These concerns and newer evidence (49) indicate an obvious risk that a health impact assessment will be misleading, sending the message to national and city-level health impact assessments that local abatement measures have no or little effect on human health. This is especially apparent in Nordic countries where the long-range transport of air pollution is often dominating over local sources. **Future research should develop methods on how the spatial scale of the exposure data should be applied for HIA and IAM.**

Several attempts have been made (including some in the Swedish air quality research programmes) to disentangle the effects of different types and sources of air pollution, without arriving in any firm conclusions. **Therefore, research on relative toxicity of particles needs to be continued to develop more specific emission control strategies.**

Organic aerosols are often a dominant species of PM$_{2.5}$, and there is an urgent need to understand the nature and sources of this type of aerosol. A particular type of organic aerosols, the secondary organic aerosols, are formed through a very complex gas-phase reactions in the atmosphere and originate from both natural and anthropogenic emissions, of which little is known. **One major issue is to identify the causal biochemical mechanisms driving the effects of air pollution on human health, particularly for secondary organic aerosols.** Clarification of these mechanisms require synthesis and cohesion of experimental and epidemiological studies.
With respect to atmospheric chemistry transport and air pollution dispersion modelling and exposure assessments, it is important to develop the analytical tools with the aim to analyse exposure to particles from specific source sectors, such as residential combustion of solid fuels, and particle number vs. particle mass and chemical composition. It is also important that the analysis can separate exposure to coarse and fine particles; “fresh” primary particles from “old” secondary; road, break, & tire wear particles from engine exhaust particles. Here, the representation of secondary organic aerosols is particularly important. The relative importance of health effects of particles from road and vehicle wear will increase drastically as the road traffic is electrified, and specific studies of particle toxicity in this area is warranted. As per usual, the model developments needs to be evaluated together with observations for more accurate exposure estimates. Future research should also promote the use of source-specific exposure-response functions in HIA and IAM.

7.2.6 Improving our understanding of particles known as condensables

Emission inventories are a large and prevailing problem for the type of particles grouped as condensable organic compounds. The current European official emission inventory under EMEP is today lacking these compounds for many sectors, and to what extent countries include condensables in the national emission reports is unknown. A large unfinanced effort to improve models and emission data is starting up in TFMM and TFEIP, based on a measurement campaign conducted in a cooperation between ACTRIS, EMEP and EUCAARI. Such improvements with respect to condensables are needed since they would give new possibilities for understanding the impacts of organic aerosols on human health.

7.2.7 What are the health effects from NO2-exposure?

Despite decades of studies, the separate health effects of NO2 from PM exposure, the specific effects of long-term exposure to NO2 also needs to be elucidated further. The experts in the UK Committee on the Medical Effects of Air Pollution (COMEAP) were in 2018 unable to reach a consensus view on the independence of the association of mortality with NO2-exposure and with PM-exposure (217). It was concluded that more research is needed. To understand the reasons for the substantial between-study heterogeneity in hazard-ratios in mortality studies, there is a need of further studies of errors in exposure assessment, especially how modelled concentrations relate to personal exposures. Multi-pollutant epidemiological studies are necessary, performed at sites with weak correlations between NO2 and PM or with improved statistical methods to handle highly correlated exposures. Chamber studies with repeated exposure to variations in combinations of ultrafine particles, other pollutants and NO2 in the same setup are needed to disentangle the effects and to study mechanisms. Additionally, the methods to quantify the effects of air pollution mixtures need to be improved. This requires epidemiological studies to obtain more detailed data on, e.g., covariance information from multipollutant models.

Further studies of the association between outdoor NO2 exposure and the incidence of asthma in adults, controlling for traffic related PM, would also be useful. There is substantial evidence linking NO2 exposure to asthma exacerbations. And recently, convincing evidence of the association between NO2 exposure and asthma incidence in children has been presented. But for adults the evidence of these possible, perhaps even likely, association is currently not sufficient for inclusion in health impact assessments such as the Global Burden of Disease work.
7.2.8 Is there a threshold in air pollution effects?
The last decades health effects of air pollution exposure have been observed at successively lower exposure levels, and even consistently showed stronger exposure-response function where the exposure is lowest. The indications that health responses to exposure is stronger in low concentration environments needs to be pursued further since non-linearity and a possible threshold drastically affects the results of any health impact assessment.

However, it is also instrumental to disentangle possible effects of other spatially distributed health risks, such as environmental noise, lack of access to green spaces and socioeconomical deprivation, and their possible relations to air pollution. In addition, clarification of-, and reduction of-, socioeconomic differences in environmental exposure are also important for long-term social sustainability.

A major and unfortunate barrier to the large-scale big-data epidemiology research needed to resolve the questions above, is researchers’ ability to access to existing registry data. For researchers, the difficulty to access registry data has increased drastically the last decade. For non-research purposes, access to data such as addresses and geocodes are publicly available. But for environmental health research purposes, a significant and increasing amount of time and effort is currently spent trying to get access to such data. Several Swedish and Scandinavian research collaborations risk failure due to these new legal obstacles regarding sharing data between countries (and especially with countries outside of the EU).

7.3. What’s so clean about clean energy? (SDG Goal 7, NEQO Clean Air, Reduced Climate Impact, Zero Eutrophication, Only Natural Acidification)
The energy sector of the industrialised world is today going through rapid changes, mainly driven by climate change and its policy responses. The overall objective is to decrease and cease the use of fossil fuels. The actions most often have a double benefit – they reduce emissions of greenhouse gases as well as of air pollutants. But not all climate actions have air pollution benefits. The replacement of fossil fuels with wood combustion will often result in higher emissions of particles, with consequences for human health.

The energy sector also covers issues related to the use of energy for industrial purposes as well as for transportation. And with the ongoing efforts to use hydrogen technologies in industry and electricity in transport sector, the sectors are more and more integrated. Since the air pollution and climate actions within the energy sector to a large extent are associated with political decisions (regulations, bonus-malus, subsidies etc.) the use of cost-benefit analysis has become an important and useful tool to give scientific support to policymakers. Since there are large differences in relative costs between many of the available measures, there exists large potential benefits for society by improving accuracy of CBAs used for policy support.

7.3.1 What are the economic costs of emission reduction measures?
Because of the 2013 change in methodology for cost-benefit analyses for the EU Clean Air Policy Package, there is an increasing need for more detailed data on costs and benefits of control measures. Due to the increased precision of the new methodology, missing data on effects, costs, and benefits of emission control measures can have a significant impact on the results of
the analysis, and thus recommendations to policymakers. Previous research within SCAC and in other projects provides indications that several – currently omitted - measures and environmental effects can be quantified and monetized. Measures such as environmentally friendly heating in small fireplaces, increased use of carpools, shift from car to bicycle, and effects such as nitrogen deposition to the Baltic Sea, are all examples of omitted measures and effects, for which existing knowledge allows impact assessment and monetization. The most stressing challenge now is to broaden the perspective on what counts as costs of behavioural change measures. In addition to include the usual techno-economic costs of measures, one should now also include cost items such as the welfare value of time, the value of uncertainty, the value of inconvenience, and other welfare economic aspects of emission control measures. Since these challenges need to be solved prior to behavioural changes can be included in integrated assessment models, this type of research is instrumental for any future consideration of behavioural changes with the same level of importance as the technical measures. These challenges are also there for integrated assessment models focused on climate change.

7.3.2 Social acceptance and reduction potential estimates for behavioural change measures aimed at small-scale wood combustion

One way to start sorting out welfare costs for non-conventional and non-technical measures to reduce emissions is through acceptance studies. Techno-economic models show that replacement of old stoves and fireplaces with new ones is a cost-effective measure to reduce emissions from small-scale wood burning. But these measures are aimed primarily at individuals and households, and individuals are, according to existing knowledge, incentivised also by many other driving forces than economic cost efficiency. It is not clear that the cheapest measure will be the preferable. At the same time, it seems that these measures often are very unpopular, which is well indicated by the strong popular opposition to the Ministry of the Environment’s 2018 proposal to ban the secondary market for stoves and other types of fireplaces. At the same time, based on Ajzen (218), it can be theorized that measures aimed at fireplaces are behaviourally suitable measures as there is a direct feedback between measure and effect (less smoke, less odour). However, there is a need for more knowledge on household responses to authority initiatives before seriously considering implementing stove-replacement programmes. What is people’s relationship to the use of wood stoves? What norms are expressed through wood burning? Are these norms strong or weak? What willingness to adapt is there? What is the perceived feeling of self-control? What motivation / intention is there to change combustion behaviour?

There is a general need for methods to estimate the expected outcome of implementation of air pollution control methods that are based on behavioural changes. One method available to study acceptance is discrete choice experiments. A benefit of such experiments is that they recently also have been used to estimate implementation potentials (upscale potential) of behavioural change measures (219, 220).
7.4 Air quality in cities of tomorrow (SDG Goal 11, NEQO Clean Air, Reduced Climate Impact)

Globally as well as in Sweden, a larger share of the population are moving into cities. In 2014, global estimates showed that more individuals lived in urban areas than in rural areas. And by 2050 some 70% of the world population is projected to live in cities. At the same time, it is well known that much of the air pollution in a city originates from sources outside the city limits. Further, the source sectors of air pollution outside the city are often different from the source sectors within the city. To add to the complexity, some emission control measures shift the source of emissions. One prominent example is electrification of transport, for which vehicle exhaust emissions in some cases is replaced mainly by emissions from large scale fossil fuel power plants. Further, air pollution is not the only stressor causing health effects in cities. In addition, there are multiple and often covarying stressors affecting the wellbeing of city life, including access to green areas, ambient noise and pollution. But cities also enables access to much more data from various sources, data that can help finetune pollution abatement strategies.

7.4.2 Health effects from increased electrification, use of biofuels, and other changes in the transport sector

An electrified vehicle fleet, increased use of biofuels, and changes in transport patterns may impact human exposure to ground-level ozone and particles. A broad implementation of alternative propulsion systems may lead to decreased concentrations of combustion particles and nitrogen oxides in background air, whereas it might, at least locally, also lead to weaker decrease or even raised ozone concentrations in densely populated areas. Due to the increased weight of vehicles with batteries, emissions of road wear particles might increase (221), and at higher speeds also road traffic noise. Further, transferring heavy motorised traffic to active modes of transport such as bikes, could instead have synergistic effects on health since this will reduce both emissions of air pollution and road traffic noise, as well as improve health through increased physical activity.

A further challenge is that the transport sector is becoming integrated with the energy sector. Traditionally, the outcome of measures within the transport system has often been analysed separated from the energy system. However, with the current increased electrification of the transport system, these systems are becoming closely linked. For this reason, the effect on air pollution of the future conversion of the transport system needs to be investigated. Here it is reasonable to assume that the rate of electrification will be uneven, with some roads and areas experiencing large electrification, whilst others remain traditional. If studies would start early, electrification thereby might provide an interesting natural experiment of the effect of electrification on emissions and human health.

Emissions of ozone-forming VOC and NOx have decreased over the last decades, leading to a decrease in episodic high ozone concentrations while low and medium percentiles have increased. In addition, ground-level ozone concentration has a strong seasonal variation with highest concentration in spring and early summer. Spring is also a time when the population is impacted by a multitude of other hazardous factors such as viruses, dust particles from road wear and agricultural fields, pollen, and lower physiological antioxidant levels. For ozone-
related effects risks, it is thus motivated to study temporal aspects associated with transport and outdoor activities. A combination of high resolution chemical models and local downscaling models will be needed to accurately describe the impact of ozone on health under different emission scenarios (such as the newly developed CLAIR- \(O_3\)-model (222)). For particle-related challenges, further analysis of the electrifications’ effect on vehicle weights and transport patterns is needed.

There is a lack of knowledge related to health effects from renewable fuel engine exhausts. The best available knowledge indicates that renewable fuels will do nothing, or very little, to solve the air pollution problem in cities. From a health perspective it is thus motivated to compare different climate policy scenarios for the transport sector with respect to their effect on human health, including analysis of biofuels, modal shifts from cars to active transports or public transport, and reduced transport demand.

Important future challenges related to the effects of electrification, biofuels and changes in transport patterns on ground-level ozone and particles include: will a warmer climate result in more frequent outdoor activities and/or opening of windows thus resulting in higher ozone and particle exposure? Will ozone exposure increase in urban environments, due to less ozone titration as the vehicle fleet is electrified? How will the seasonal variation in ozone exposure change in the future, will there continue to be a strong spring peak, and how will it impact human health considering other factors and activities such as winter sports? What is the effect on emissions and concentrations from increased electrification, considering road/tire/break wear particles and the use of studded tires? What other transport scenarios can achieve desirable climate- as well as air quality effects?

7.4.3 Integrated assessment of environmental stressors in the urban environment, including climate change

In addition to effects from air pollution, other negative non-communicable health effects in urban environments are caused by noise, urban heat islands, and lack of green surfaces: all covarying with air pollution in an urban environment. Especially noise has been gaining attention since recent research has shown correlations between long-term exposure to noise and increased risk for myocardial infarction, stroke, diabetes, and obesity. A clear example of covariation of air pollution and noise comes from recently decided reliefs in national guideline values for exposure to traffic noise in newly constructed dwellings. Such decisions affect exposure to noise but also to air pollution since it is possible to build dwellings closer to roads. Even though covariation effects are very likely, studies related to sustainable urban environments still needs further improvement to better consider this.

Another area of integration that needs improvement is regional energy transitions in national studies. In south Sweden a large proportion of the levels of fine particles originates from other countries, where use of coal and oil for heating or power generation is more common than in Sweden. A transition to sustainable energy sources in surrounding countries would have substantial effects on Swedish air quality and public health.

Furthermore, climate change has effects on emissions but also dispersion of air pollution. Future trends in ground-level ozone will be impacted by emissions of natural and
anthropogenic emissions of both VOC and NOx, but also by climate change. If situations with very low wind speeds become more frequent as a result of climate change, this will have a strong influence on local air quality in areas with high traffic emission density. **It is important to integrate scenario analysis of urban climate with analysis of urban air pollution, especially for traffic pollutants.**

7.4.4 Data fusion for improved description of population exposure

Dispersion modelling at different scales is often applied to produce high resolution concentration maps, sometimes in combination with monitoring at stationary sites using some type of data fusion. A large number of new sensors are today available to measure concentrations of air pollution at lower cost, potentially allowing more dense networks of sensors (223). Although most low-cost sensors available today do not fulfil the performance requirements of reference monitoring stations (224), they may be a valuable complement if used in combination with dispersion model results. Machine learning and AI are commonly used to calibrate low-cost sensors making them more comparable with reference monitoring stations. A fusion of data from sensors, both mobile and stationary, and dispersion models has the potential to dramatically increase both accuracy and spatial resolution of concentration and exposure assessments (225).

Air quality forecasts and different forms of data assimilation is another rapidly developing and promising application of machine learning and AI (226). While being very promising, the use of sensor-technology in combination with dispersion model results is still at the beginning and will require further research involving atmospheric sciences, sensor technology and data science. **Significantly increased precision and accuracy of air pollution concentration maps would offer a unique support for targeted AQ assessments and control and for the communication with citizens.**

7.4.5 Policy integration over different administrative levels.

In many cities much effort is spent on urban planning, incl. measures to reduce exposure and to meet air quality requirements. At the same time, urban planners don’t consider that local air quality can be remedied with measures outside the city border (and vice versa), and the net effect of multiple local initiatives can be omitted by international stakeholders. Therefore, air quality and urban development strategies risk becoming sub-optimal. **To support urban air pollution strategies, available opportunities at the various administration levels need to be investigated and appropriate decision support models developed.** Such models are not yet fully developed, although promising initiatives have been presented for India (227) and northern Italy (219), as well as in emission dispersion models for Europe (228). A model approach that would give relevant support to policy makers should be able to weigh cost-effective measures at the city level against cost-effective measures at the national or international administrative level. This type of model would require a new type of cost optimization, adapted to emission dispersion models capable to consider distribution between administrative levels.
Further alignment and integration of climate change and air pollution research and policy (SDG Goal 13, NEQO Reduced Climate Impact, Clean Air)

Climate change will, as mentioned under several SDGs, influence air quality. Future air pollution policies need therefore to be aligned or integrated with climate policies – both with respect to emissions and control as well as with respect to changes in climate and adaptation. So far, air pollution has only to a limited extent been considered in this respect. And when taken into account, it has mostly been by air pollution scientists and policy makers, but not from climate scientists and policy makers. If history is any indication, initiatives in linking air pollution and climate change research will even in the future mostly be taken from the air pollution side.

Aerosol effects on precipitation and climate change effects on aerosol formation
As previously mentioned, aerosols have a disproportionally large influence on precipitation compared to greenhouse gases. Aerosols also affect solar radiation directly and indirectly through changes in cloud cover and cloud properties. But how future changes in aerosol concentrations will affect cloud formation, precipitation and the partitioning between liquid and ice precipitation needs to be further studied.

Another important area for research is how climate change may increase the global emissions of dust particles. The uncertainty related to the dust climate feedback is large and is for the direct climate effect estimated to range between −0.04 to +0.02 Wm⁻²K⁻¹. This direct feedback is enhanced close to major source regions and could play an important role in shaping the future climates of Northern Africa, the Sahel, the Mediterranean region, the Middle East and Central Asia (229). Dust interactions with clouds induce a variety of indirect effects, but more knowledge is needed regarding whether dust–cloud interactions warm or cool the climate. The lack of quantitative understanding of dust indirect effects is especially problematic for understanding dust–climate feedbacks at high latitudes, where dust–cryosphere and dust–cloud interactions are likely to dominate over direct radiative effects.

Is there a need for additional measures to abate an underestimated climate penalty?
Warm, sunny, and dry weather with weak winds is favourable for ozone formation and the occurrence of episodes with high ozone concentrations. Climate change increases the likelihood of such weather conditions, and subsequent increased ozone levels (so called climate penalty). Based on observations, researchers have shown that there was a significant climate penalty from ground-level ozone during the extremely dry and hot year 2018 (72), much stronger than concluded through earlier modelling studies in for example CLEO (59, 63). Therefore, it is important to update modelling studies to better capture intertwined effects of ground-level ozone and climate change.

Today, one can improve future air pollution scenarios to include processes that were lacking in previous climate penalty studies, including drought having negative impacts on the vegetation cover and its ozone uptake, as well as wildfire emissions scenarios. It is also possible to use up-to-date climate and air pollution emission scenarios with higher geographical model resolution linked to current legislation and modern technical advancement. Previously 50°50 km grid cells were used, today 3°9 km are available. There is a need to further investigate whether additional measures are necessary to abate future climate penalty on air pollution in
Sweden, what the climate penalty will be under various weather conditions (normal vs extreme), and whether benefits from lower emissions of ozone precursors will be counteracted by climate change. Further, it is important to study risks of wildfires and corresponding effects on ground-level ozone and particles as well as forest management practices that would reduce such risks. Methane emissions induced by melting permafrost will impact background ozone levels and this needs also to be investigated.

7.5.3 The role of ozone in climate change mitigation

The Swedish forests sequester in the order of 35-45 Megaton CO$_2$-equivalents per year, which can be compared to the emissions from all other sectors in Sweden of 50-70 Megatons per year. This sequestration is mainly due to the gap between the forest growth and harvest rates. If the adverse impacts of ozone will decrease, then the growth of the Swedish forests would increase even further, leading to an increased carbon sequestration of Swedish forests under the assumption that harvest rates are constant. Furthermore, an increase in harvested wood products should also contribute to climate change mitigation. But the extent to which decreased ozone concentrations will increase biomass growth is not established and it is therefore important to correctly estimate the ozone impacts on forest growth and establish consensus to provide solid advice to forest management and air pollution policy makers.

7.5.4 Air pollution and greenhouse gas policy instruments in the Nordic region

Most air pollutants directly or indirectly affect climate change. NO$_x$-VOC produces ozone, which is warming, S, N and organic condensing compounds give particles that cool while soot heats. Model calculations show that you get a global warming of about 0.3 degrees, and about 1 degree in the Arctic, if you reduce the global emissions of S, OC and soot by about 80% (230). The most beneficial emission reduction with respect to climate is that of spring-time soot (231).

All the above-mentioned air pollutants are mainly originating from fossil fuel combustion and are thus associated with CO$_2$ emissions. However, most applied climate policy analysis for CO$_2$ control currently omits climate effects of air pollutants, which renders a risk of misguided and ineffective policy. It is therefore obvious that integrated analysis of climate and air pollution measures and instruments are needed to achieve the best and most cost-effective effect for both climate and air quality. An example is the link between the Nordic Renewable Electricity Certificate system, which indirectly incentivise air pollution emissions and the EU NEC Directive which sets national targets for the same pollutants. Vice versa, it is important to analyse whether instruments needed to reach the targets in the NEC reduction commitments will affect CO$_2$ emissions. Another important assessment is the analysis of how changes or prolongation of the certificate system might affect emissions of CO$_2$ and air pollutants.

As mentioned above, all air pollutants handled within the Gothenburg Protocol and the NEC Directive have an impact on global warming. The heating potential from soot is positive and about 3-10 times greater per kilo of emissions than the corresponding cooling potential from the other air pollutants. On the other hand, the total amount of soot is much lower than the emissions of the other air pollutants. When also including the fact that the relative mix of cooling and warming particle fractions varies over sectors and technologies it is evident that there are opportunities for climate-neutral air pollution control strategies, prospects necessary to explore.
On a more aggregated level it is also important to analyse how sector-wide climate targets affect emission of air pollutants, air quality, and climate change. Sweden has a long-term strategy to reduce Sweden’s net greenhouse gas emissions to zero by 2045. Such a reduction will have an impact on Swedish air pollution. Since Nordic climate strategies often include increased use of biofuels, and since ‘complementary measures’ (outside Swedish borders) can constitute up to 15% of 1990 emissions in the Swedish climate strategy, there are good reasons to investigate effects of existing and upcoming national CO₂ strategies on the overall emissions of air pollutants.

7.5.5 What are the socio-economic costs of the climate effects of air pollution?
As mentioned earlier, CBAs are becoming more important as decision support tools for policy makers. Today, given the common omission of air pollution climate impact in climate change impact assessments, also applied socio-economic assessments of climate change policy instruments are incomplete. Further still, often climate change impact assessment omits effects on air quality, and other environmental effects, despite plenty of available scientific evidence. Vice versa, applied air quality policy instrument analysis is incomplete with respect to the effect of these instruments on climate change, again despite an abundance of evidence. Furthermore, recent improvements in the scientific and epidemiological understanding of human health and ecosystem effects of air quality policy measures are yet to be considered in socio-economic assessments.

Correspondingly, it is important for assessments in applied ex-ante and ex-post policy instrument analysis to be aligned with current economic-, scientific- (incl. epidemiological) understanding of the effects of greenhouse gas and air pollution emission control. More specifically, it is important to analyse both long- and short-term effects of greenhouse gas and air pollutant emissions for different assumptions on economic growth and to ensure consistency of air pollution CBAs with climate IAMs. It is also important to add monetary estimates of climate effects of greenhouse gases and air pollutants acting as SLCFs into CBAs.

7.6. Clean air to maintain terrestrial biodiversity and the productivity of forests and agricultural land (SDG Goal 15, NEQO Zero Eutrophication)
Although air pollution is a minor driver in the ongoing degradation of biodiversity, it is in several land ecosystems large enough for observable ecosystem changes being induced by changing air pollution levels. But given ongoing environmental changes brought on by global economic development and climate change, the dynamics of the air pollution linkages with biodiversity is at risk of changing. Based on earlier research the focus here is on further exploration of ozone and nitrogen effects on biodiversity, as well as on ammonia and agriculture, including integrated measures to reduce emissions of ammonia and methane.

7.6.1 Understanding the dynamics of future ozone concentrations in ecosystems
The ongoing changes in ozone concentrations also have important implications for vegetation ozone exposure. As a reminder, it has been shown that there is an ongoing trend in ozone concentration patterns: with a shift in spring peak concentrations towards earlier in the year,
and a decrease in the summer concentrations of ozone. A parallel and overlapping shift in the start of the vegetation growing season has also occurred. The interaction between ozone concentration and start of growing season is important for the accumulated vegetation dose of ozone over the course of the year. Furthermore, the change in the ozone concentrations will result in a more “chronic” ozone exposure of vegetation to mid-range ozone concentrations. **The consequences of this future chronic ozone exposure on vegetation need to be evaluated.**

7.6.2 Further development of the POD-index used to estimate vegetation exposure to ozone

The development of the index based on leaf ozone uptake, i.e. the POD, represented a major step for improving the representation of ozone impacts on vegetation for the different bioregions across Europe. However, the current POD approach assumes that all ozone molecules taken up to the leaf interior have equal negative impacts on plant metabolism, grain production and growth. It also assumes that the effect of the ozone molecules is independent of time-of-year or the physiological state of the plant. However, plants have considerable antioxidant capacities. It is therefore important to **further develop the index of leaf ozone uptake to quantitatively consider the ozone detoxification capacity of the leaf in an improved exposure index.**

Recently, maps have become available for ambient air conditions for the estimates of POD for some forest tree species in Sweden (232). If combining these maps with dose-response relationships presented in the Air Convention Mapping Manual, it can be estimated that current ozone levels in southern Sweden would cause a yearly biomass growth reduction for European silver birch of between 18 and 37%. This is obviously unrealistic. Similar unrealistic growth reductions would be estimated for Norway spruce.

Why is there an obvious discrepancy between the estimated POD values in southern Sweden and the estimated biomass reductions stated for trees in the Mapping Manual? One explanation could be that an ozone molecule that is taken up to the interior of leaves and needles under field conditions does not have the same negative impact on plant metabolism and growth as a corresponding ozone molecule taken up by the young trees under experimental conditions. **Hence, there is an obvious need to complement laboratory experiments and look more closely into the impact estimates associated with the ozone uptake to leaves and needles of forest trees.** Earlier studies made under the research programmes SCAC could not establish negative impacts of ozone on forest growth, but also established that larger samples at plot-level resolution would be necessary for solid results. Fortunately, today the ozone exposure as well as the nitrogen deposition, to plot-level forest stands can be estimated with a much higher accuracy than in the earlier studies.

If focusing on crops instead of forests, there is a much stronger agreement between observations and modelling results. But most studies have been made on wheat, and **validation with experimental data and observations of such results is essential and should continue, especially for other crops than wheat.** Other important areas, where ozone risk assessment for crops needs development include a more mechanistic representation of growth and developmental processes and inclusion of quality and food safety/security aspects in the modelling of ozone effects. Here, the senescence-promoting effect of ozone needs
consideration. In addition, extension of the ozone risk assessments to include effects of global change, including warming, altered soil humidity and elevated CO\textsubscript{2} concentrations needs to be initiated.

7.6.3 Nitrogen cycle, ecosystem impacts and re-emission of ammonia

Nitrogen impacts ecosystems in multiple ways, and one and the same molecule of reactive nitrogen released to the environment can be transformed into several forms in sequence and impact a cascade of processes in air, soil and water before it is finally transformed to N\textsubscript{2} gas and re-enters the atmosphere. To assess the impact of nitrogen on ecosystems requires multidisciplinary approach and co-operation between specialists on biogeochemistry, climate change and biodiversity. Similarly, the effects of nitrogen are difficult to understand without considering interactions with other elements, most notably with carbon and with phosphorus. This need is perhaps most obvious in modelling the effects of nitrogen where understanding and conceptualizing the carbon cycling in soils and plants plays a key role. Our ability to model the impact of nitrogen on ecosystems is still limited due to the complexity of the issue. Here, to increase predictive capability of current models, further research is needed on nitrogen and carbon (and phosphorus) interactions and on impact of nitrogen on biodiversity. Apart from air pollution two other drivers of change that need to be considered are changing climate and land use. Future research on air pollution effects on ecosystems need to consider interactions between nitrogen and carbon and other nutrients/pollutants and multiple drivers of change.

Ammonia emissions have not decreased as strongly as other air pollutants, and the associated nitrogen deposition has a strong negative impact on ecosystems, biodiversity, and human health. Various nitrogen compounds are also important for climate change. In addition, climate change also has the potential of further releasing ammonia to the air, but the strength of this process needs to be investigated. Another atmospheric process that needs further research is the potential that climate change increases the long-range transport of ammonia from emission source regions such as the Benelux further north to pristine areas in Fennoscandia and the Arctic. Such a process would constitute a potential climate penalty for reduced nitrogen deposition and further hinder achievement of several NEQOs.

Nitrogen-related research is covering a whole cascade of processes; from NO\textsubscript{x} and NH\textsubscript{3} emissions via atmospheric transport to deposition and ecosystem interactions, re-emissions and even direct influence on climate through N\textsubscript{2}O (11). This research includes understanding and implementing processes involved in emission after fertilizing, and re-emission of ammonia after deposition inter alia. There are many remaining research challenges but one of particular interest for the NEQOs is how much the national and international ammonia emissions need to be decreased to mitigate a potential climate penalty.

7.6.4 Integrated analysis of measures to reduce greenhouse gas and air pollution emissions from the agricultural industry

The agricultural industry is the source of large emissions of ammonia and methane. Emissions of both pollutants are driven by household food consumption, in particular consumption of meat. However, food consumption patterns appear currently to be changing in Sweden towards a larger share of vegetables. Effective ammonia and methane emission reduction measures can be found in all parts of the food product life cycle, and research is needed on the net
**effect of measures at the agricultural industry versus the final consumer.** As per usual, the challenge is complicated further by the ongoing climate change.

### 7.7. Integrated challenges transgressing SDG and NEQO objectives

There are several research initiatives that do not fit the frame set by the SDGs. These can be characterised as focusing on integration of science and policy and ensuring research consistency over the long term.

#### 7.7.1 Expand the integration of air quality management into the Swedish work by the Agenda 2030-delegation, the Swedish Climate Policy Council, and the Swedish Council for Sustainable Cities

From a systems perspective, Swedish and European air pollution-related research has for almost two decades focused on the links between climate change and air pollution. This research has clarified that there are plenty of opportunities for synergies between air and climate (combustion-free electricity, heat, & transport production, energy efficiencies, etc.) but that there are also plenty of risks of conflicts (small-scale use of bioenergy, diesel-powered cars, increased extraction of biofuels from forests, increased ecosystem sensitivity to air pollutants and changed dispersion patterns of air pollutants due to climate change, etc.). But as the Swedish energy sector and large parts of Swedish industry are largely already fossil-free, it is mainly in the iron and steel industry, the cement industry, the forestry and agriculture industry, the transport sector, urban planning, and small-scale heating, that domestic policy has much to gain from further integration between air and climate policy. A society in constant change always requires research to further develop the understanding of how air quality is affected by the continuous development of the industrial and areal sectors. Climate adaptation measures may also be of importance to consider with respect to air quality. Future research should therefore clarify how the Swedish adaptation activities affects air quality and other environmental goals.

#### 7.7.2 Continued scientific support of international processes and agreements

Swedish air pollution research has since the 1980-ies actively contributed with research results and expertise to the Air Convention and during later decades to the EU work on air quality. The Air Convention relies on active bottom-up international research collaboration and it is still of crucial importance for the Convention’s success that parties continue to support the knowledge development and contribute in various expert bodies. Sweden and Swedish research are well represented and there is a mutual interest that this representation and its close connection to scientific research continues. The increasing interest of going beyond the geographical scope of the Convention and collaborate with other regions in the world will also increase the demands on the scientific community. Finally, experience from the various processes under the Convention, including the importance of integrated analysis of environmental challenges and solutions, provides useful input to the challenge of contributing to the UN SDGs.

The Air Convention Gothenburg Protocol sets 2020 as a policy target. Since 2020 has now passed, a review is ongoing. The result of the review will be available by 2022 or early 2023 and will give guidance on whether stricter emission targets are needed to protect human health and
the environment from dangerous levels of air pollution. Another process that can be expected is some sort of update of the EU Air Quality Directive, which had 2010 as a target year for achievement of agreed air quality standards (whilst allowing some flexibility). Both the review and the update will rely on updated WHO guideline values for air quality which are expected to be published in autumn summer 2021.

The review of the Gothenburg protocol and probable update of the AQ Directive indicates a need for stricter targets, objectives, and regulations. Thus, further efforts in applied research will be of urgent need. Policymakers will need solid updated input on effect targets and control options to assure that European and Swedish air quality policy is aligned with the UN SDGs.
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THE RESEARCHERS PARTICIPATING IN THE PROGRAMMES AND CONTRIBUTING TO THE PROGRAMME REPORTS


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