**Narrative for the e-learning course on air pollution effects work under the Convention**

## 1. Introduction

### 1.1 Welcome

Welcome to the e-learning course on air pollution effects work under the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention). We thank Germany, xxx and xxxx for financially supporting the development of this course.

### 1.2 Course overview

The course will describe the main effects of air pollution and guide you through the effects-related work under the Convention, including methodologies to assess effects. The course is recommended for employees of Ministries and technical institutes dealing with the Convention, academics, NGOs, and anyone interested in work on air pollution effects. To learn more about the Convention itself, we recommend you take the e-learning starter course on the Convention first.

### 1.3 Navigation tips

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### 1.4 Learning objectives

After completing this course, you will be able to:
1. Identify the main effects of air pollution
2. Outline the objectives of the effects-related work under the Convention
3. Describe different methods to assess air pollution effects
4. Identify first steps to take in effects assessments to support policy making effectively

## 2. Effects-related work under the Convention

### 2.1 The Convention

The UNECE Convention on Long-range Transboundary Air Pollution has helped control and reduce emissions of air pollutants since 1979 to protect human health and the environment. The protocols under the Convention set emission reduction commitments for pollutants, such as sulphur dioxide ($SO_2$), nitrogen oxides (NOx), ammonia ($NH_3$), volatile organic compounds (VOCs), particulate matter (PM 2.5), persistent organic pollutants (POPs), and heavy metals (cadmium (Cd), lead (Pb) and mercury (Hg)). They also set emission limit values for different sources of air pollution, for example for mobile sources, such as cars; for stationary sources, such as power plants and industrial facilities; measures for area sources, such as agriculture, and for different industrial products and processes.

Most of the protocols, such as the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, are effect-based, meaning that reduction obligations are based on target thresholds for ecosystems and health, which could cause long-term damage.

The collective effort of Parties to the Convention has resulted in a significant reduction of harmful pollutants: Since 1990, sulphur emissions in the region have been reduced by 80 per cent and nitrogen oxide emissions by more than 50 per cent. In particular, the decrease in sulphur emissions has led to [[Heleen de Wit: improved water chemistry (reduced acidification / chemical recovery of) in lakes and rivers and thereby better conditions for aquatic life (in particular fish and (macro-invertebrates) insects,), and to healthier soils [Ulf Grandin: and surface waters] and therefore reduced effects of acidification on land ecosystems].[healthier soils and surface waters. Recovery of forests and lakes from acidification have led to better conditions for fish and insects.] Decoupling of economic growth and air pollution trends has prevented 600,000 premature deaths annually. Average life expectancy has increased by 12 months, thanks to emission reductions.

For more information, we recommend you take the e-learning starter course on the Air Convention.

### 2.2 The Working Group on Effects

Scientific evidence that acid rain and acidification of lakes and rivers was caused by air pollutants, emitted far away from where they caused damage, brought the topic of transboundary air pollution on the political agenda in the 1970s. Early in the discussions on the Convention, it was therefore recognized that understanding and quantification of the harmful effects of air pollution was a prerequisite for reaching agreement on effective pollution control. To develop the necessary international cooperation in the research on and the monitoring of pollutant effects, the Working Group on Effects (WGE) was established under the Convention in 1980.

The Working Group on Effects provides information on the degree, temporal trends, and geographic extent of the impacts of major air pollutants on human health and the environment. Its six International Cooperative Programmes (ICPs) and the Task Force on Health identify the most endangered areas, ecosystems and other receptors by considering damage to human health, forests, lakes, rivers, plants, materials and cultural heritage

Over the years, the Working Group on Effects has developed dynamically. The understanding of effects of air pollutants on ecosystems has increased and permitted to identify emerging challenges. The Working Group has developed and maintained an extensive international network of scientists of various disciplines, helping to build of a common knowledge base. The direct exchange between scientists and policymakers has led to innovative approaches creating mutual trust and learning. More information on the ongoing work under the Working Group on Effects can be found in chapter 4.

## 3. Effects on..

Before we take a look at the negative effects of air pollution, let's recap what causes air pollution: Emissions of harmful substances from different natural and anthropogenic sources cause air pollution. The pathways of pollutants in the atmosphere are influenced by transport, dispersion, and deposition, which vary based on factors such as climate and meteorological conditions, emission heights, geographical features, sources, and chemical properties. In the atmosphere, pollutants mix, dilute, accumulate, undergo chemical changes, and are removed from the atmosphere by deposition with precipitation, through sedimentation and gaseous interactions with surfaces (soil, leaves, buildings). The pollutants can lead to direct exposure and damage, for instance through leave damage in crops, corrosion of glass and metals, and through inhaling, to human health. Alternatively, damage can occur through further processing, accumulation and chemical change in soils, leading to changes in nutrient access or mobilization of toxic elements and thereby causing damage to trees and other vegetation, and in downstream lakes and rivers. plants Air pollutants can also be transported over long distances across national borders and affect ecosystems and people's health and ecosystems far away from their point of emission, for instance in arctic and mountainous regions but also urban environments. This complexity makes it necessary to design high-quality monitoring networks of air pollution and its effects on a transboundary basis with and harmonized methodologies, and find solutions through international collaboration.

There are many negative impacts of air pollution on the environment, human health and the economy . To reduce these negative impacts of air pollution, policies for reducing emissions of pollutants to the atmosphere are essential. To inform and develop policies and to assess whether these policies have their intended effect, monitoring programs on health and environment are key.

**3.1 Human health**
Air pollution is a major environmental health threat globally. Air pollution causes diseases, ranging from asthma to cancer, cardiovascular and respiratory disease, and the evidence is growing for other health effects, such as metabolic disorders. It is the largest contributor to the burden of disease from the environment, according to the World Health Organization; ambient and household air pollution accounts for 7 million deaths around the world every year.

Air pollution is a complex mixture of gaseous and particulate pollutants that affect human health. Particulate matter is of major health concern, as it can lead to severe respiratory and cardiovascular diseases; small particles (PM2.5) can penetrate the lungs when you breathe them in and go into your blood stream. Other pollutants, like, nitrogen oxides, sulphur dioxide and volatile organic compounds affect mainly the respiratory system, leading to respiratory diseases, such as asthma and lung infections. Nitrogen oxides also causes heart diseases and blood and spleen disorders. Ozone reduces lung function, causes asthma, and leads to fatigue and headaches. Persistent organic pollutants are a group of pollutants that accumulate in your body; many are carcinogenic and can affect reproductive health. Heavy metals are toxic and lead to neurological disorders and malfunctioning of vital organs. Both extent and duration of the exposure to air pollutants influence health outcomes. Important are also vulnerabilities related to age, general health status, coexisting diseases, etc.

**3.2 Terrestrial ecosystems**
Air pollution can damage all plants, trees, herbs, grasses and mosses. It may also have negative impact on the nutrient status in ecosystems. Damage can include impacts on plant growth and health, such as effects on biodiversity and habitat quality. All types of ecosystems are affected: coastal habitats, mire, bog and fen habitats, grassland, heathland, scrub and tundra habitats, and forest and woodland.

**Acidification and eutrophication of soils**
Emissions of sulphur, nitrogen and other compounds, deposited to forests and other ecosystems, lead to acidification of acid-sensitive soils. This can lead to leaching of aluminium and removal of minerals and other nutrients from the soil. These nutrients are then no longer available for uptake by plants making it difficult for them to survive.

Nitrogen deposition may also cause an excess in soil nutrients, which is called eutrophication. Eutrophication of soils often increases plant productivity and causes changes in physiology and growth rates that vary among species. The changing growth rates alter competitive species interactions, with those ones that are adapted to nitrogen-rich environments outcompeting those that are not, and lead to a decrease in biodiversity.

**Direct effects of air pollutants on vegetation**
Excessive exposure to atmospheric pollutants has harmful effects on many types of vegetation and the ecosystem and food services that vegetation provides. The effects vary between vegetation type or species and pollutant and include changes in vitality and growth for trees and (semi-)natural vegetation, yield (quality and quantity) for crops, flower number and seed production for (semi-)natural vegetation, and vulnerability to abiotic stresses such as frost or drought and biotic stresses such as pests and diseases. For example, increased ground-level ozone causes damage to cell membranes in plants inhibiting photosynthesis and hence their growth.

**3.3 Water quality**
Water quality is affected by air pollution in different ways. Pollutant loading to surface waters can cause acidification and eutrophication. Heavy metals and persistent organic pollutants can contaminate the water and the aquatic food web, and cause harm to aquatic life and those who

depend on it: wildlife and humans. All types of water ecosystems are affected: inland surface waters, streams and marine habitats.

**Acidification of rivers and lakes**

When water moves from acidified soils into streams and lakes, it also causes acidification of surface waters. This soil solution has a low pH and high aluminium content and when it leaches into lakes and rivers, it can suffocate fish and insects by accumulating on gills and reducing their respiratory function. Loss of fish populations, in particular salmon, and other sensitive species from acidification reduces the biodiversity of lakes and rivers. Long-term effects of acid deposition will lead to depletion of calcium from soils, rendering these ecosystems and the lakes in them even more sensitive to acidification.

**Eutrophication**

As in soils, deposition of nitrogen oxides and ammonium (NHx) can also cause the eutrophication in water bodies. In agriculturally-impacted lakes and rivers, which are usually rich in nutrient phosphorus, eutrophication is largely caused by phosphorus and can cause algae blooms and ultimately a loss of oxygen, and of aquatic life. Algae blooms may also cause release of algal toxins, which may be poisonous to animals and humans. In natural lakes and rivers, which are usually rather low in phosphorus, additional nitrogen from air pollution can lead to increased algal growth and changes in biological diversity. Also, marine ecosystems are very sensitive to nitrogen pollution. Depending on the location, and in addition to the inflow with rivers nitrogen, inputs from the atmosphere have a relevant contribution to algal blooms and anoxic zones.

**3.4 Food production**

Food production is an important driver of air pollution. However, air pollution can also impact food production.

**Impacts on soil quality and fisheries**

While nitrogen is an important nutrient and needed to grow crops, much of the nitrogen (in the form of manure and fertilizers) poured onto fields is being lost to the environment (nitrogen use efficiency); a large amount is washed from fields to groundwater and into rivers or lost to air. This affects soil quality and thus the very capacity of the soil to sustain plant productivity. Fisheries are also affected as nitrogen run-off from land creates dead zones, degrading habitat for fish already vulnerable because of over-fishing and climate change.

**Ozone causing crop damage**

When ozone enters the leaves of a plant, it can reduce photosynthesis, which can lead to a slowing of plant growth, reduction in defense against disease and insects, and a loss of below ground root function. Over the long-term, these combined effects can reduce the overall health of the plant and result in it being replaced by less ozone-sensitive species. This can alter habitat quality and nutrient and water cycles, with special impacts during the growing season. This is particularly important for food production, as the most ozone-sensitive crops are all staple foods for most of the world's population. For example, ozone is estimated to cause relative global crop losses for soybean (12%), wheat (7%), maize (6%) and rice (4%).

**3.5 Materials and cultural Heritage**

Air pollution not only harms human health and the environment but it also contributes to the degradation of surfaces of historical buildings and monuments. The impact air pollution from anthropogenic sources on materials is enormous and can cause effects from visually impacting the appearance of our cultural heritage to their premature deterioration. In addition, corrosion (caused by sulphur and nitrogen compounds) and soiling (caused by particulate matter) can lead to severe economic losses.

### 3.6 Climate change

Air pollution and climate change are closely related because air pollutants and greenhouse gases are often co-emitted by the same sources, for example burning of fossil fuels and agriculture. Both air and climate-relevant substances are also emitted into the same atmosphere, creating further interactions. Some air pollutants can have climate effects by affecting the amount of incoming sunlight that is reflected or absorbed by the atmosphere, with some pollutants warming and others cooling the Earth. These so-called short-lived climate pollutants (ozone, methane, black carbon) remain in the atmosphere for a shorter period of time than carbon dioxide (CO2), but have, in comparison to CO2, a much higher global warming potential.

**Climate effects on air quality and interactions with air pollution effects**

A warmer atmosphere will have implications for air quality, as it is expected that more ozone is formed, affecting our health, climate, crops and ecosystems (see above). Climate change also leads to interactions with air pollution effects on different receptors. For example, in addition to air pollution pressures, forests are increasingly threatened by climate change-related factors, reducing forest vitality, which may lead to reduced growth and carbon sequestration, thus further exacerbating climate change.

### 3.7 Economic development

Air pollution takes its toll on the economy in several ways: it costs human lives, it reduces people's ability to work, it affects vital products like food, it damages cultural monuments, it reduces the ability of ecosystems to perform functions societies need and it costs money in remediation or restoration. According to the Organisation for Economic Co-operation and Development, the estimated economic cost of air pollution is increasing and could rise to 1% of global GDP by 2060 – around USD 2.6 trillion annually – as a result of sick days, medical bills and reduced agricultural output, unless further action is taken. The economic benefits (avoided costs) from pollution reduction hence largely outweigh the relatively small abatement costs.

## 4 Methodologies to assess effects

As mentioned before, assessing and monitoring effects of air pollution is important for the development of air pollution control policies and for the effectiveness assessment of these policies. In the context of the Convention, policy-relevant information on effects are used to build consensus about emission reduction targets for the protocols and to evaluate their impacts.

Research on and insights into the effects of air pollution are important to inform policymakers and the public about risks for the environment and human health, the relationship between pollutant loads and impacts (dose-response relations), and damage evaluations. Monitoring effects also provides the input for model development and validation, which can then provide information on trends on the effectiveness of air pollution abatement policies, and on projections that can show the need for further policy measures.

Under the Convention, air pollution effects monitoring is organized as follows:
Monitoring of concentrations and the transport of air pollution is organized under the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP).

The Working Group on Effects conducts receptor-specific air quality monitoring and effect observation at the receptor-level.

The following will outline monitoring methodologies and activities in further detail.

The monitoring of effects of air pollution under the Convention is organised by six International Cooperative Programmes (ICPs) and the Task Force on Health, which are coordinating networks of monitoring sites across countries and are using a common and harmonized methodology. They collect data on forests (including forest soils), crops and seminatural vegetation, natural lakes and rivers, and materials and cultural heritage. This has enabled the development of comprehensive databases on the effects of air pollution on ecosystem vitality, biodiversity and productivity, corrosion of materials and human health. Long-term monitoring has also provided scientific evidence that the measures taken to reduce air pollution have their intended effect, i.e. ecosystem recovery, reduced corrosion of materials and reduced burden of disease.

Last but not least, the data and methodologies are also used for purposes outside the Convention, for instance, in European Union research and directives and other monitoring networks in Europe (e.g., the Long-term Ecosystem Research Network in Europe) and beyond (e.g., the Acid Deposition Monitoring Network in East Asia).

**4.1 Monitoring air quality**

Air quality monitoring is the process of measuring the concentration levels of various pollutants and particles in the air to assess its quality. Air quality monitoring is important to assess exposure and impacts on health, ecosystems, vegetation, materials and climate. It can provide data that can drive policymaking and help with assessing compliance with air quality regulations. Monitoring data can also be used to raise public awareness and help the public make informed decisions.

**4.1.1 Monitoring of background concentrations and depositions**

In the context of the Convention, monitoring of air quality is mainly carried out through a network of background monitoring stations under the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) in the UNECE region. The objective of monitoring air quality under EMEP is to measure background deposition and concentration levels of air pollution and to track the long-range transport of air pollutants. To achieve this, EMEP stations are placed in rural or remote areas far from direct pollution sources to capture background concentrations that are representative of larger regions rather than local hotspots.

EMEP stations use a variety of sophisticated instruments to measure different air pollutants and environmental parameters, e.g. gas analysers, chemical speciation instruments, gravimetric samplers, aerosol counters, deposition collectors, and analytical instruments. Monitoring requirements are outlined in the EMEP monitoring strategy.

**4.1.2 Receptor-specific air quality monitoring**

In addition to area-wide air quality monitoring, air quality monitoring is also used to measure concentrations, depositions and fluxes at the receptor hence at very specific locations. Depending on the objective of the monitoring, the location of the monitoring site needs to be decided upon: e.g. schools or residential areas in cities if specific populations are to be protected; forests or wetlands that are either exposed to air pollution or that need to be protected in the long-term, monuments and cultural heritage sites for materials. The objective of this type of monitoring is to assess the direct impact of pollutants at these targeted receptors, understand their exposure levels, and set up dose-response relations. Depending on the receptor that is being observed, monitoring methods can vary. Instruments are set up directly at or near the receptor.

#### 4.1.2.1 Concentration monitoring

When carried out in forests or other non-urban areas, air pollution concentration monitoring at the receptor level is often carried out through passive sampling. Passive sampling devices collect pollutants over time, relying on natural diffusion processes and operating without electricity, making them suitable to be deployed in remote areas. The collected sample is then analyzed in a laboratory.

For example, ICP Forests measures ozone, sulphur dioxide and nitrogen oxides by means of passive samplers at dozens of forests sites across Europe. Monitoring methods are outlined in the ICP Forests Manual.

#### 4.1.2.2 Deposition monitoring

Monitoring the deposition of air pollutants involves measuring the amount and types of pollutants that settle from the atmosphere to the Earth's surface. This process helps assess the impact of air pollution on the environment and human health. There are two main types of deposition: wet and dry. Wet deposition is measured by collecting rainwater to analyze dissolved pollutants, sampling of snow or fog to determine the concentration of pollutants. For dry deposition, pollutants that settle on surfaces like soil, water bodies, vegetation or materials can be measured. Flux measurement can be used to measure the rate at which pollutants are deposited onto surfaces. A common deposition monitoring method that does not require electricity is a bulk precipitation sampler. The device is continuously open and also samples gases and particles deposited on the funnel surface. Another method is a wet-only sampler, which only opens during precipitation events. Samples then need to be analyzed.

ICP Forests monitors deposition by bulk and wet-only samplers outside and beneath the forest canopy. The objective is to quantify concentration and fluxes of main nutrients and air pollutants across the forest ecosystem: for this, open-field, throughfall (deposition passing through the canopy via precipitation, washed from leaves and branches) and stemflow (precipitation running down tree trunks capturing pollutants deposited on its surface) measurements are carried out at dozens of intensive monitoring sites. Throughfall and stemflow deposition together gives an estimate of the deposition to the forest floor. For further information about deposition methodologies, check the ICP Forests Manual.

Another method of deposition monitoring is to use vegetation, such as naturally growing mosses as biomonitors of atmospheric deposition of pollutants, such as heavy metals, nitrogen, and persistent organic pollutants, to assess spatial pollution concentration patterns and temporal trends across a region.

Since 1990, ICP Vegetation has sampled mosses every five years. For further information, check the ICP Vegetation moss survey protocol.

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#### 4.1.2.3 Air quality monitoring in urban areas

To protect public health, air pollutant levels are monitored in urban areas. Real-time air quality data is used to inform the public and issue health advisories and alerts. Monitoring methods in urban areas can be sophisticated and include continuous monitoring stations with advanced analyzers for real-time measurements of pollutants and mobile monitoring units.

### 4.2 Effect observation at the receptor-level

To monitor the response of different receptors to air pollution, effect observations at the receptor level is important. This ensures assessing the conditions of different receptors with the aim of detecting the rate, the trend, the extent, and intensity of changes in ecosystems and materials due to air pollution.

#### 4.2.1 Chemistry in soil and water

Monitoring air pollutants in soils and water can provide important information about soil and water chemistry and help in understanding environmental changes and impacts on local biota.

##### 4.2.1.1 Soil

The purpose of soil monitoring is to characterize the chemical status of forest soil and its changes over time as a response to pollutants and to assess soil properties that determine the sensitivity of soils to atmospheric pollution. It can be useful to monitor tree nutrition, soil and soil solution. For tree nutrition, foliage is collected in regular intervals from the upper tree canopy and analyzed for main nutrients and heavy metals (every 2 years). For the solid part of soil monitoring, soil samples are obtained on a periodical basis (10 to 20 years) and analyzed for their chemical content and acidity. Soil solution is obtained by lysimeters (a device to study the transport of water and material through the soil), and analysis carried out with an ideal frequency of two-weeks to quantify pH, conductivity, nutrients and heavy metals.

ICP Forests monitors forest soils. For more information, check the ICP Forests Manual on litterfall, soil and soil solution.

##### 4.2.1.2 Soil water

Monitoring soil water chemistry (e.g. with a suction cup sampler) can also provide important information about geohydrochemical interactions with biological effects. Acidic water percolating through the soil dissolves and weathers minerals, releasing base cations for nutrient uptake by microbes and roots alike, seeping into deeper layers and ground water, and ultimately outflowing to rivers and lakes. Soil water is intimately coupled with the chemical and biological processes in the upper soil layers.

ICP Integrated Monitoring provides physical, chemical and biological measurements in a defined area. For more information on methodologies, check the ICP IM Manual.

##### 4.2.1.3 Water

Monitoring trends in water chemistry is important to understand effects of air pollution on freshwater ecosystems and to link chemical dose with biological response. For example, when monitoring acidification, the determinants monitored include those that define the degree of acidification, or which are directly related to acidification of the waters (pH, alkalinity, inorganic aluminium, major cations and anions, nitrogen species, dissolved organic matter). For assessing effects of air pollution, the Acid Neutralizing Capacity (ANC), defined as the potential of a solution to neutralise additions of strong acids to a given level, is a useful parameter. Trace metals and persistent organic pollutants can also be monitored.

ICP Waters is monitoring water chemistry. For more information on ICP Waters chemical monitoring methods, check the ICP Waters Manual.

#### 4.2.2 Biota

Monitoring the changes in animal and plant life in a specific region is important to understand the impacts of air pollution. Different types of biological monitoring are used to identify damage to plants, areas at risk of adverse impacts from air pollution, and populations of species that are particularly sensitive to certain pollutants. For example, indicator species are particularly sensitive to specific pollutants and can serve as early warning signs of environmental changes. Some organisms accumulate high levels of pollutants, providing insights into long-term exposure and ecosystem health, e.g. fish. In addition, analyzing species richness and abundance (e.g. population sizes in a defined area) and community composition can help in detecting changes caused by air pollution.

**4.2.2.1 Habitat conditions and plant communities**

Monitoring of vegetation aims to assess and quantify bioindicative responses to changes in pollutant deposition or other atmospheric factors, e. g. warming, by careful monitoring species assemblages in relatively small and well-defined catchments. In addition, vegetation structure and species cover are also monitored to follow any major changes in the structure and species composition of plant communities across the whole monitoring site. The data also gives insights on plant diversity of trees, shrubs and field and bottom layer species. Observation data also show dynamics of tree biomass and canopy structure. Data on dead trees, logs and stumps are useful to follow the decay process and the dead wood as habitat for fungi, mosses, and insects.

ICP Integrated Monitoring carries out vegetation monitoring through intensive plot observation. Methodologies are outlined in the ICP IM Manual.

**4.2.2.2 Morphological changes in vegetation**

Morphological assessments can help in examining physical changes in organisms, such as leaf damage in plants and reductions in biomass. This can provide information about plant and ecosystem health and the effect of air pollution as a stressor.

**Plant tissue**

Ozone causes visible injury on the leaves of sensitive plant species. Typically, injury is present between the veins on the older leaves, with small bronze, brown, or yellow flecks appearing on the upper surface. Visible-leaf injury is a visual indication of ozone stress. This may not always result in quantifiable reductions in growth of native plants or yield of crops. In contrast, alterations in plant physiology including reductions in growth, flowering, seed production and crop yield can occur in the absence of any visible leaf-injury symptoms. Therefore, identification of visible ozone symptoms can be a quick and relatively simple way to tell if a plant is potentially being damaged by ozone. To monitor ozone damage to vegetation, including damage on crops, field surveys can be carried out. Biomonitoring experiments, whereby specific ozone-sensitive plant species such as white clover are monitored can also provide important data.

ICP Vegetation monitors ozone damage to vegetation. It has also developed a smart-phone App for recording incidences of ozone-induced injury on vegetation, with the aim to create a database of injury records from around the world, adding to the growing list of ozone-sensitive plant species. For further information, please check the ICP Vegetation Ozone Monitoring Protocol.

**Crown condition**

Monitoring crown condition is an important aspect of assessing forest health and the vitality of individual trees. The crown of a tree, which includes the branches and foliage, is sensitive to environmental stressors such as air pollution, pests, diseases, and climate change. By evaluating the condition of the crown, researchers can gather valuable information about the overall health of forest ecosystems and the impact of various stress factors. Trained observers evaluate crown condition using standardized protocols. They assess factors like density, transparency, discoloration, and dieback based on visual inspection.

ICP Forests assesses crown condition as part of its monitoring programme on health, growth, diversity and chemical condition of forests across Europe since 1980s. For more information check ICP Forests Manual on visual assessment of crown condition and damaging agents.

#### 4.2.2.3 Aquatic biota

Monitoring of fish populations, invertebrates and algae which show different tolerance and response to acidity from sulphur or nitrogen pollution provide important bioindication of water chemistry conditions. For example, to monitor aquatic biota for acidification effects, species or communities sensitive or tolerant to acid conditions will be selected. As the geographical distribution of species and sensitivities throughout life stages vary, universal indicators are not always available. Nevertheless, species/acidity relationships are recognised, and a limited degree of universality or identification of common indicators is possible. For example, a number of species are known to be sensitive to acid conditions and their presence/absence will indicate both current and recent past water conditions. For any water body to be sampled, these organisms should be sought and identified unequivocally to species level. Data on changes in these populations can thus be important indicators of water quality. The most common species that are monitored are invertebrates since these have a short life cycle and thus are sensitive to relatively quick changes in their chemical environment. Fish populations react more slowly to changing water chemistry (older fish tolerate more than younger, implying that the young disappear first). If the entire population of a river or lake becomes extinct, recolonization might be difficult because of lacking source populations to draw from.

Regarding contamination with trace metals/heavy metals, in particular Hg, and persistent organic pollutants (POPs), water chemical concentrations can be rather low. The bio-concentration, -accumulation and -magnification in biota, however, enable us to measure these components and assess their risk for exposure higher up in the food web. Many fish species are relatively long lived, which means they will bio-accumulate environmental pollution like trace metals and POPs to a much higher degree than i.a. the rather short-lived invertebrates and are thus selected as biomonitors for assessing pollution levels of trace metals/heavy metals and POPs.

ICP Waters monitors biological effects of air pollution on freshwaters. For more information on ICP Waters biological monitoring methods, check the ICP Waters Manual.

### 4.2.3. Materials

Materials exposed to air pollutants undergo chemical reactions that can cause corrosion, discoloration, surface erosion, and structural weakening. Monitoring these effects is crucial for the preservation of buildings, monuments, infrastructure, and other valuable materials. Monitoring of exposure of materials to different pollutants can be performed at specific field exposure test sites, where samples of different materials (e.g. stone, aluminium glass) etc. are placed on test panels and observed over extended periods. In addition, air pollutant concentrations are measured with passive samplers at the test sites. Samples are then analyzed in a laboratory.

ICP Materials monitors materials at network of test sites throughout Europe. For further information about methodologies, check the ICP Materials Manual.

### 4.2.4. Health

Health impact monitoring involves systematically assessing and analyzing the effects of air pollutants on public health. It aims to identify, quantify, and understand the health outcomes associated with exposure to air pollutants. Some of the methods used in health impact assessment are epidemiological studies, health surveillance, biomonitoring and exposure assessment. Epidemiological studies help in investigating the correlation between air pollutant levels and health outcomes (e.g., respiratory and cardiovascular diseases). Health surveillance involves monitoring hospital admissions, emergency visits, and mortality rates related to air quality. Biomonitoring describes the methods to analyze blood, urine, or tissues of individuals to detect exposure to pollutants. Exposure assessment involves assessing pollutant concentrations in the air at locations where people live, e.g. in urban areas.

For example, the Task Force on Health works to identify and assess the health risks and impacts of air pollution. It reviews evidence on how air pollutants affect human health, thereby helping to set priorities for future monitoring and reduction strategies. Tools, such as AirQ+ and CLIMAQ-H (Climate Change Mitigation, Air Quality and Health) have been developed to support quantification of health risks and impacts of air pollution.

#### 4.3. Identifying pollutant thresholds

The monitoring of air pollutants and its effects and scientific research on pollutants, their pathways and interactions in the environment help to set-up dose-response relations and inform the establishment of air pollutant thresholds for different receptors. Air pollution thresholds describe pollutant-specific concentrations for different receptors that, when exceeded, can harm human health, ecosystems, crops and materials. These thresholds are important tools for the development of policies as they can identify ecosystems and populations at risk. They are defined in the Manual on methodologies and criteria for Modelling and Mapping Critical Loads & Levels and Air Pollution Effects, Risks and Trends and in the WHO Air Quality Guidelines.

#### 4.3.1. Critical loads and levels

In the context of the Convention, the concepts of critical loads and levels have been developed to describe air pollutant thresholds. Critical loads and levels are defined as the atmospheric deposition or concentration of atmospheric pollutants below which adverse effects on receptors such as human beings, plants, ecosystems or materials do not occur according to present scientific knowledge. A critical load refers to deposition of pollutants, while a critical level refers to pollutant concentrations in the atmosphere, which usually have direct effects on vegetation or human health. The basic idea of the critical load approach is to balance the depositions to which an ecosystem is exposed with the capacity of that ecosystem to buffer the input, or to remove it from the system without causing harmful effects inside or outside the system.

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When pollutant loads (or concentrations) exceed the critical load (or critical level) it is considered that there is risk of harmful effects. The excess over the critical load or level has been termed the exceedance. A larger exceedance is often considered to pose a greater risk of damage.

Critical loads and levels and their exceedances are commonly used as indicators of the effects of air pollution on various receptors. They can be applied site-specifically for a single ecosystem or on the national or regional level. The Convention, based on scientific knowledge, has defined deposition threshold values (Critical Loads) for terrestrial and aquatic ecosystems for several pollutants, e.g. sulphur, nitrogen and heavy metals. They are based on a steady-state concept, meaning they are the constant depositions an ecosystem can tolerate in the long run. Also, concentration or flux based Critical Levels have been defined for various pollutants such as Ozone, ammonia, sulphur dioxide or nitrogen oxide. Critical loads and levels provide a reference point for the sustainability of air pollution against which actual as well as modelled future pollution levels can be compared. Critical loads and levels have been designed to support the setting of ambition levels and to assess the effectiveness of air pollution reduction policies. For more information, check the manual on methodologies and criteria for modelling and mapping critical loads and levels and air pollution effects, risks and trends.

#### 4.3.2. Empirical critical loads

One way to establish critical loads is to derive ecosystem specific critical loads, e.g. for nitrogen, from observations and experiments. Such critical loads are called empirical critical loads for nitrogen (CLempN). CLempN are in almost all cases based on observed changes in the structure and functioning of ecosystems, primarily in species abundance, composition and/or diversity, and nitrogen leaching, decomposition or mineralisation rate. In addition, many of these CLempN are a suitable indicator to identify risks and damages to biodiversity at the ecosystem level. For example, as a result of eutrophication from nitrogen deposition, changes in nitrogen availability affect the population size of a species, leading to changes in the composition of biological communities and ecosystems. By evaluating these effects in experiments, it is possible to establish dose-response relationships and confirm that excessive nitrogen deposition negatively affects species assemblages and thus poses a serious threat to biodiversity. In total, there are CLempN for more than 50 different ecosystem types. They can be selected and attributed to a suitable ecosystem from an existing overview table. The empirical Critical Loads are expressed in kilogram per hectare and year and given in ranges. The scientific report, where those values are published, offers assistance to select a specific value from that range. For more information, please check the easy-to-understand brochure or the comprehensive, scientific report on empirical critical loads of nitrogen.

**4.3.3 Modelled critical loads based on simple mass balance calculations**

Critical loads can also be calculated with the use of models. This offers the opportunity for area-wide application and attribution of thresholds to such ecosystems for which no empirical Critical Loads exist. Furthermore, while the empirical Critical Loads set thresholds for the deposition of nitrogen from the atmosphere, through the calculation of Critical Loads, thresholds can also be set for the deposition of sulphur into ecosystems to prevent acidification. The model-based approach to calculate critical loads uses mathematical equations to link a target concentration in the soil or in the water (critical limit) with the maximum amount of pollutant deposition that will not cause significant harm to a specific receptor in the environment. In practice, the target concentration serves as proxy for biological criteria, for example the vitality of a tree or the abundance of earthworms in the soil. Simple chemical models that describe the whole chain from deposition to biological impact are used for these purposes. Basic input, which is needed for the models, is land cover data, soil type data, knowledge on forest growth and meteorological and hydrological data. More details of this methodology are given in the Manual on methodologies and criteria for modelling and mapping critical loads and levels and air pollution effects, risks and trends

**4.3.4 Critical levels for vegetation**

To protect vegetation from the harmful effects of high air concentration, for nitrogen oxide (NOx), sulphur dioxide (SO2) and ammonia (NH3) recommendations are made for concentration-based critical levels. For SO2 there are four categories of vegetation types. Threshold values are defined for sensitive groups of lichens, for forest ecosystems, (semi-)natural vegetation and for agricultural crops.

The critical levels for NOx are based on the sum of the NO and NO2 concentrations. Separate critical levels were not set for different classes of vegetation because of the lack of available information, however, the following ranking of sensitivity was established: (semi-)natural vegetation is more sensitive towards NOx than forests and crops.
The critical levels for ammonia refer to ecosystems with the most sensitive lichens and bryophytes and to ecosystems with vascular plants. Lichens and bryophyte species are found to be more sensitive than vascular plants.

For ozone, there are critical levels for crops, (semi-)natural vegetation and forest trees. Two main types of critical levels have been developed: concentration-based critical levels that are based on the concentration of ozone in the air immediately above the plant (AOT40); and flux-based critical levels that are based on the amount of hazardous ozone entering the leaves of plants. Ozone fluxes are calculated using knowledge of how climate, soil factors and plant factors influence the opening and closing of the stomatal pores on the leaf surface. For more information, check the ICP Vegetation Manual.

#### 4.3.5. Acceptable levels for materials

The monitoring work of ICP Materials has resulted in dose-response functions, which link the dose of pollution, measured in ambient concentration and/or deposition, to the rate of material corrosion or soiling. This has led to the development of a classification system for corrosivity of environments, for mapping of areas with increased risk of corrosion, and for calculation of cost of damage caused by deterioration of materials. Models capable of scenario assessment and future predictions have also been developed. On the basis of these models, critical loads have been defined, which may be considered as tolerable, based on technical, economic, and social considerations.

#### 4.3.6. WHO Air Quality Guidelines

The WHO Air quality guidelines are a set of evidence-based recommendations of limit values for specific air pollutants developed to help countries achieve air quality that protects public health. The WHO Air quality guidelines recommend levels and interim targets for common air pollutants: PM, O3, NO2, and SO2.They are based on based on expert evaluation of current scientific evidence.

### 4.4. Spatial and temporal assessments

Maps of critical loads and levels and their exceedances combine spatial information on receptors, pollutants and critical loads and levels. They are used to show the potential extent of pollution damage, to define areas at risk. They also deliver important input for the development of strategies for reducing pollution. Decreasing pollutant deposition below the critical load is seen as the means for preventing the risk of damage. In practice, maps of critical loads have been used as yardsticks to assess the need for reducing depositions. In combination with deposition maps and emission data, maps of critical loads and levels and their exceedances provide critical information for the policymaking process.

Models can also show how ecosystems change over time and provide important information about timescales for ecosystem recovery.

#### 4.4.1 Critical Load and critical level maps

With the means of a landcover map or a receptor map it gets possible to attribute Critical Loads and Levels to a regional or national map, that shows the sensitivity of ecosystems and vegetation towards air pollution. For Critical Loads such maps can be based on empirical Critical Loads or on modelled Critical Loads. Resolution and uncertainty is driven by the input data, such as landcover, soil or climate maps.

A simple approach on a national level to display the sensitivity of ecosystems towards nitrogen deposition is, to take the list of empirical critical loads and form an attribution to a national ecosystem distribution map. Also, such an attribution can be done with Critical Levels for ammonia, nitrogen oxide or sulphur. If on the national level a national ecosystem distribution map is not available yet, the European receptor map, published by the Coordination Center for Effects under the ICP Modelling & Mapping, provides a good starting point for European countries and EECCA countries.

A more complex approach for Critical Load mapping is to combine national soil-, landcover-, receptor- and climate-maps and use it for simple mass balance Critical Load calculation. Those maps provide area wide information on ecosystem sensitivity. Simple mass balance calculations can be done for nitrogen and sulphur effects. Those calculated maps might include information on sensitivity of ecosystems in such areas where no empirical Critical Load could be attributed with the above-mentioned approach.

Critical Load maps are used in policy making by combining them with area-wide deposition maps of the related air pollutant. area wide deposition maps are modelled with atmospheric chemical transport models. Such deposition data requires well developed modelling capacities and therefore is not available in every country on the basis of national modelling. However, EMEP provides deposition data the European and EECCA countries. In a geostatistical approach Critical Loads are being substracted from deposition fields. Resulting exceedance maps show the areas where deposition of a pollutant is higher than the sensitivity of an ecosystem. This indicates how large pollution is and on which areas policy should focus on.

#### 4.4.2 Other area-wide assessments

Critical Levels for Ozone

To display the area wide sensitivity of vegetation towards Ozone, national or regional maps of AOT40 or the flux-based Critical Levels for Ozone can be modelled…..

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Materials

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ICP Waters, ICP IM? ICP Forests

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#### 4.4.3 Dynamic modelling

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Dynamic modelling is the logical extension of critical loads. Critical loads are based on a steady-state concept, representing the constant levels of pollutant depositions an ecosystem can tolerate in the long run, once it has balanced out with those depositions. However, many ecosystems are not in equilibrium with present or future depositions, since there are processes at work – so-called buffer mechanisms – which delay reaching equilibrium. These delays can last for years, decades, or even centuries. Critical loads do not account for these time scales. Dynamic models are necessary to evaluate the time it takes for ecosystems to recover when critical loads are no longer exceeded and to assess the time it takes for damage to occur when critical loads continue to be exceeded.

Dynamic models are used to show how properties of ecosystems change over time. For example, ICP Integrated Monitoring uses dynamic models to determine the timescale of the ecosystem recovery (e.g. soil, water) from acidification or eutrophication. Physical and chemical data and long-time series of observations of input and output fluxes for key sites are used to assess model performance and to identify uncertainties.

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## 5. Use in policymaking

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The information and quantified data that is collected through the monitoring of air quality, deposition and effects of air pollution and through the modelling of critical loads and levels and their exceedances provide important information for the policymaking process.

### 5.1 Area wide indicators: areas at risk

On the national or regional level the knowledge about the sensitivity of receptors, about their status and about the level of existing pollution may inform about the need to reduce emission in a certain region. For the CLRTAP the Coordination Center for Effects provides European maps of Critical Loads Exceedance for eutrophication and acidification and based on that national data statistics on the area at risk. On the European level and in many countries the percentage of exceedance data is used in a temporal resolution as an indicator of how the status of ecosystems at risk through air pollution develops over the time. For example in Germany maps and statistics of Critical Load Exceedance for Eutrophication are one of the indicators under Germany's sustainable development strategy.

### 5.2 Local decision support

In many countries of the CLRTAP, Critical Loads are applied on the local level to determine eutrophication status, and to estimate nitrogen exceedances in relevant natural and semi-natural ecosystems. In several countries Critical Loads are used as part of national standardised guidelines for the determination and assessment of the impact of nitrogen deposition on nearby ecosystems caused by installations requiring immission control approval. In Germany for example, the assessments are carried out for facilities that are to be newly licensed. For all biotopes and ecosystems located in the vicinity of such a new facility, nitrogen sensitivity must be defined with the help of empirical critical loads. The German guideline is intended to contribute to a greater degree of legal certainty in the authorisation of installations and, by extension, to simplify and accelerate enforcement.

**5.3 Decision support under the Convention: integrated assessment modelling**

In the framework of the Convention, the results of the effect-related work are an essential component that feeds into integrated assessment modelling (IAM), an important decision support tool that has supported negotiation processes on emission reduction commitments by Parties.

Integrated Assessment Modelling is a comprehensive approach used to evaluate complex environmental issues, including air pollution and climate change. It combines knowledge and methods from various disciplines to assess the interactions between human activities, environmental processes, and policy measures. It is a powerful tool supporting informed decision-making through comprehensive analysis and scenario development.

The integrated assessment model that has been developed under the Convention is the Greenhouse Gas Air Pollution Interactions and Synergies (GAINS) model. It has the ability to address various pollutants, emission reduction alternatives, abatement costs and impacts in a consistent systematic framework. GAINS therefore provides useful information on trade-offs between pollution sources, costs and benefits of pollutant reductions as well as impacts of different pollutants on human health and the environment. It calculates future emissions for a medium-term time horizon. Emission abatement alternatives and emission control costs can be simulated taking a variety of optional emission reduction technologies into account. Data on atmospheric dispersion processes (modelled under the Convention's Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP)) and critical load and critical level data (compiled under the Working Group on Effects (Coordination Centre for Effects (CCE)) are then incorporated into the GAINS model.

In the context of the Convention, GAINS provides support to assess whether the current abatement efforts promote an appropriate improvement, i.e. reduced emissions and better air quality. It can support the decision-making process by providing predictions of future air pollution impacts under different scenarios, asses optimized allocation of emission reductions, i.e. it can help identify regions where further reductions are required to reach a specified surface water, air or forest soil quality.

**6. Key takeaways**

[to be completed, suggestions welcome]