World Health Organization
REGIONAL OFFICE FOR Europe

EUROPEAN ENVIRONMENT AND HEALTH PROCESS

Health risk assessment of air pollution

General principles

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Abstract

An air pollution health risk assessment (AP-HRA) estimates the health impact to be expected from measures that affect air quality, in different socioeconomic, environmental, and policy circumstances. As such, it is an important tool for informing public policy decisions. This document introduces the concept of AP-HRA, describes in broad terms how the health risks of outdoor air pollution and its sources are estimated, and gives an overview of the general principles for the proper conduct of an AP-HRA for various scenarios and purposes. The information is aimed at a broad audience of readers who do not need to know how to apply the tools, but seek a general understanding of the concepts, scope and principles of AP-HRA.

Keywords

AIR POLLUTION - adverse effects

AIR POLLUTION - analysis

RISK ASSESSMENT - methods

ENVIRONMENTAL MONITORING

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Contents

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Abbreviations

Aphekom	Improving Knowledge and Communication for Decision Making on Air Pollution and Health in Europe (project)
AP-HRA	air pollution health risk assessment
AQG	air quality guidelines
BenMAP	Environmental Benefits Mapping and Analysis Program
CRA	comparative risk assessment
CRF	concentration–response function
DALY	disability-adjusted life-year
EC	European Commission
EPA	Environmental Protection Agency
EU	European Union
GBD	Global Burden of Disease
HIA	health impact assessment
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
O_3	ozone
PM	particulate matter
PM_{10}	particulate matter with an aerodynamic diameter below 10 μm
$PM_{2.5}$	particulate matter with an aerodynamic diameter below 2.5 μm
REVIHAAP	review of evidence on health aspects of air pollution (project)
RR	relative risk
SO_2	sulfur dioxide
SO_x	sulfur oxides
TFH	Task Force on Health Aspects of Air Pollution
YLD	years lost due to disability
YLL	years of life lost

Executive summary

This publication introduces the concept of air pollution health risk assessment (AP-HRA), describes in broad terms how the health risks of outdoor air pollution and its sources are estimated, and gives an overview of the general principles for the proper conduct of an AP-HRA for various scenarios and purposes. The target audience includes policy-makers at the local, national and international level, and other users of health risk estimates in agencies, and research and advocacy groups.

Because the publication was prepared in the context of the work of the UNECE Convention on Long-range Transboundary Air Pollution, the emphasis is mainly on European and North American tools and references.

The main purpose of an AP-HRA is to estimate and communicate the health impact of exposure to air pollution or changes in air pollution in different socioeconomic, environmental, and policy circumstances. In many countries, an AP-HRA is formally required as part of the decision-making process for new programmes, projects, regulations, or policies that potentially have an effect on air quality. In other countries, where assessments were previously limited to qualitative descriptions, scientific advances are now allowing more detailed quantitative analyses of the health risks of air pollution. Thus an increasing number of AP-HRAs are being carried out for a variety of policy scenarios and geographical and time scales, using different methods.

A number of tools are available to conduct an AP-HRA. These tools are associated with different workloads and require different levels of expertise. In selecting a tool, it is important to first define the policy question to be answered and the audiences to be informed. The technical needs of the assessment context, such as the relevant pollutants, geographical scale and data requirements, should then be considered.

There are a number of online tools for AP-HRAs with a range of technical and operational characteristics, and incorporating functions, equations, and often datasets. Using these tools for AP-HRAs leads to better consistency, comparability and quality assurance. In selecting an AP-HRA, the aim should be to maximize scientific rigour within the resources available.

The first step of an AP-HRA is to assess the exposure of the target population to specific air pollutants. Monitoring data may be used to estimate the past and current exposure to air pollution for populations living near the monitoring site. In addition, air quality modelling is often used to estimate differences in exposure for different socioeconomic and environmental conditions within the geographical area of interest, and to predict changes in exposure in future policy scenarios.

The second step of an AP-HRA is to estimate the health risk associated with the exposure to air pollution. This requires the use of concentration–response functions (CRFs), which quantify the health impact per concentration unit of a particular air pollutant. Typically, these CRFs will have been established in epidemiological studies. Results of AP-HRAs are often reported in terms of numbers of attributable deaths or cases of disease, years of life lost, disability-adjusted life years, or change in life expectancy attributable to exposure or a change in exposure to air pollution. These

health impacts can then be used to evaluate costs and benefits of policy change in monetary terms. An important limitation of this component of the AP-HRA is the availability of baseline public health statistics for the targeted population.

The third step of an AP-HRA is to quantify and express the uncertainty of the generated estimate of health impact. This is an important and integral component of the results, and it is vital to ensure both that the main message is not lost and that the results produced are understandable by policy-makers and others who do not necessarily have a technical background or expertise in AP-HRA. The use of expert judgement (consensus) on the level of confidence of the results is recommended. In addition, the involvement of communication experts may be considered, to ensure effective communication of the AP-HRA results.

1. Introduction

1.1 Scope and purpose of this publication

This publication provides a general introduction to the concept of air pollution health risk assessment (AP-HRA) and the estimation of health risks from air pollution and its sources, and highlights general principles for conducting an AP-HRA in various policy scenarios (WHO Regional Office for Europe, 2014). Examples are presented illustrating different aspects of the topics discussed in relation to different policy questions. This publication has been prepared in the context of the UNECE Convention on Long-range Transboundary Air Pollution; the emphasis is therefore mainly on European and North American tools and references.

For more information, the report of a WHO expert meeting on AP-HRA, together with all background papers, is available online (Regional Office for Europe, 2014).

The target audience for this publication includes policy-makers at local, national and international level and other users of health risk information from various sectors in agencies and research and advocacy groups.

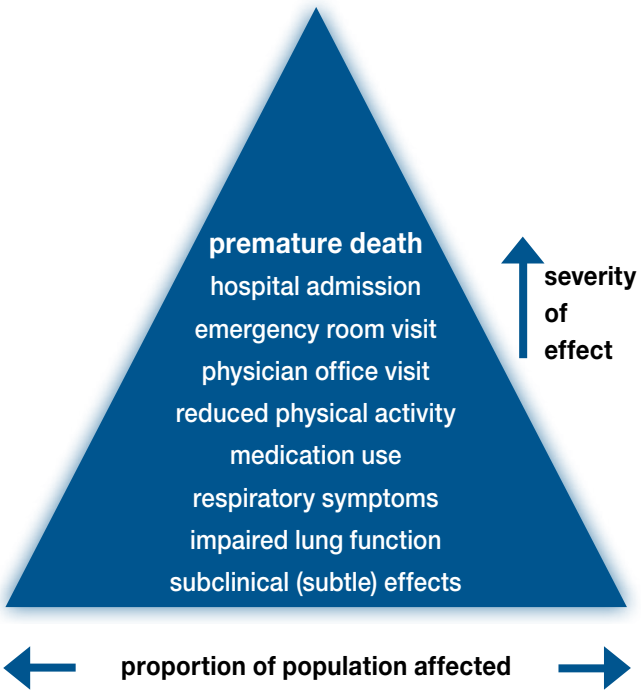
1.2 Background

Air pollution is an important determinant of health (WHO Regional Office for Europe, 2006). Numerous epidemiological studies have found an association between air pollution and a wide range of adverse health effects in the general population; the effects have ranged from subtle subclinical effects to premature death as shown in Figure 1 (Samet & Krewski, 2007).

Some groups – for example older adults, children, pregnant women and people with an underlying disease, such as asthma – may be more at risk, and may develop more severe health effects more quickly when exposed to air pollution. In addition, certain groups may be exposed to higher levels of outdoor air pollution, e.g. people living near busy traffic routes or those in specific occupational or socioeconomic groups (WHO Regional Office for Europe, 2005).

Pollution in ambient air is generally a complex mixture. Consequently, the adverse health impacts observed in

Figure 1. Air pollution health pyramid

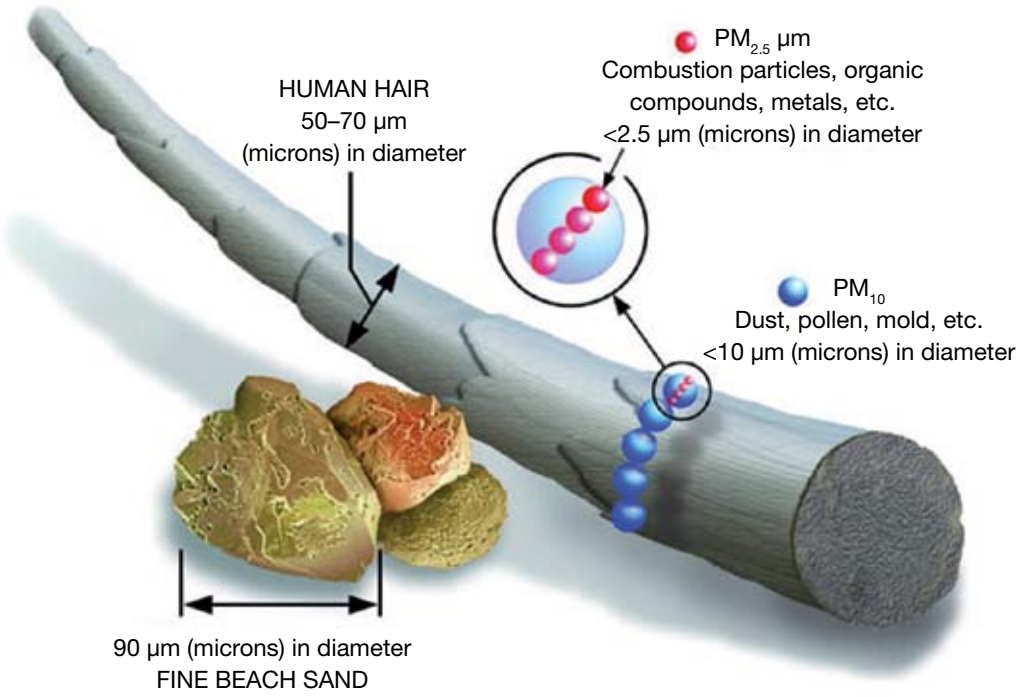


Source: adapted from Samet & Krewski (2007), reproduced by permission of Taylor & Francis Ltd.

epidemiological studies and attributed to an individual air pollutant may actually be partly due to other pollutants in the mixture. The air pollutants often investigated in these studies – particulate matter (PM), black carbon, ozone (O_3), nitrogen dioxide (NO_2), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide, heavy metals or black smoke – may be proxies for the air pollutant mixture. This issue is particularly relevant in relation to the health impact of exposure to PM in ambient air. PM originates from primary emissions (e.g. soot from combustion sources, sea salt and soil from wind-driven resuspension) and formation of secondary particles in the atmosphere. PM may be characterized in terms of the mass concentration of particles smaller than 2.5 µm ($PM_{2.5}$) or 10 µm (PM_{10}), the number of particles (ultrafine), or the chemical composition (e.g. black carbon, organic compounds and heavy metals). Epidemiological and toxicological evidence shows that PM mass ($PM_{2.5}$, PM_{10}) comprises fractions with varying types and degrees of health effects (WHO Regional Office for Europe, 2013). Different particle sizes, composition, or characteristics can be related to specific emission sources better than other air pollutants and may therefore be considered a (more) suitable indicator. Thus, PM_{10} may be an appropriate indicator when considering the impact of resuspension of road dust, while black carbon is a more sensitive indicator for exhaust emissions from road traffic (Keuken et al., 2012). It is therefore important in an AP-HRA to select the appropriate pollutants for the sources that are relevant to the exposure of the targeted population. $PM_{2.5}$ has been investigated in many epidemiological studies, and has been shown to be a robust indicator of risk associated with exposure to PM from diverse sources and in different environments (Lim et al., 2013). Figure 2 shows a schematic overview of the relative sizes of PM_{10} and $PM_{2.5}$ in relation to a human hair and fine beach sand (US EPA, 2008).

While much has been done to improve air quality and, consequently, human health in many parts of the world, evidence for

Figure 2. Schematic overview of the relative size of particulate pollution, PM_{10} and $PM_{2.5}$



Source: US EPA, 2008.

adverse health effects persists at levels below the current air quality standards and historically low levels of air pollution in many countries. In addition, air pollution is of increasing concern in many developing countries, where emissions have been rising in the absence of strict air quality policies. This has resulted in several episodes of poor air quality, in particular in urban areas (Health Effects Institute, 2010). Quantitative estimates of the health impact of air pollution have become increasingly important, to allow policy-makers and other stakeholders to devise and implement more effective local, national, and global policies to reduce air pollution.

An AP-HRA can aid this process by answering specific policy questions. Indeed, in many countries it is required as part of the decision-making process for new programmes, projects, regulations, and policies aimed at improving air quality that may affect air quality as a side-effect. In many other countries, it may be conducted as part of an assessment or research project, even though there is no legal requirement (WHO Regional Office for Europe, 2014).

1.3 What is a health risk assessment?

A health hazard can be defined as a source of risk to human health or well-being (Department of Health, 2006). A health risk assessment is the scientific evaluation of potential adverse health effects resulting from human exposure to a particular hazard. In the context of this publication, the health hazard of interest is air pollution.

An AP-HRA aims to estimate the risks of past, current or future exposure to air pollution and of changes in exposure that may result from planned policies or other modifications of air quality (Department of Health, 2006; HIP, 2014). An AP-HRA may be quantitative or qualitative; it generally assesses (i) the amount of air pollution present, i.e. pollutant concentrations, (ii) the amount of contact (exposure) of the targeted population, and (iii) how harmful the concentration is for human health, i.e. the resulting health risks to the exposed population (WHO, 2010). The estimates provided by an AP-HRA are intended to inform the decisions of policy-makers or other stakeholders.

The required input data for an AP-HRA (e.g. air pollution, baseline health statistics, CRFs of air pollutants) are not always available, and many risk assessments have to be based on estimates or judgements of some of the data inputs or characterizations. As a result, HRA outcomes generally have associated uncertainties, which should be characterized as far as possible (WHO, 2010). It should also be noted that AP-HRAs generally include only the subset of health impacts that can be quantified, and do not deal with other health effects for which no CRF is available. Ideally, to protect public health, an AP-HRA should be as inclusive as possible; however, in most cases, it is likely that the HRA will underestimate the actual risk.

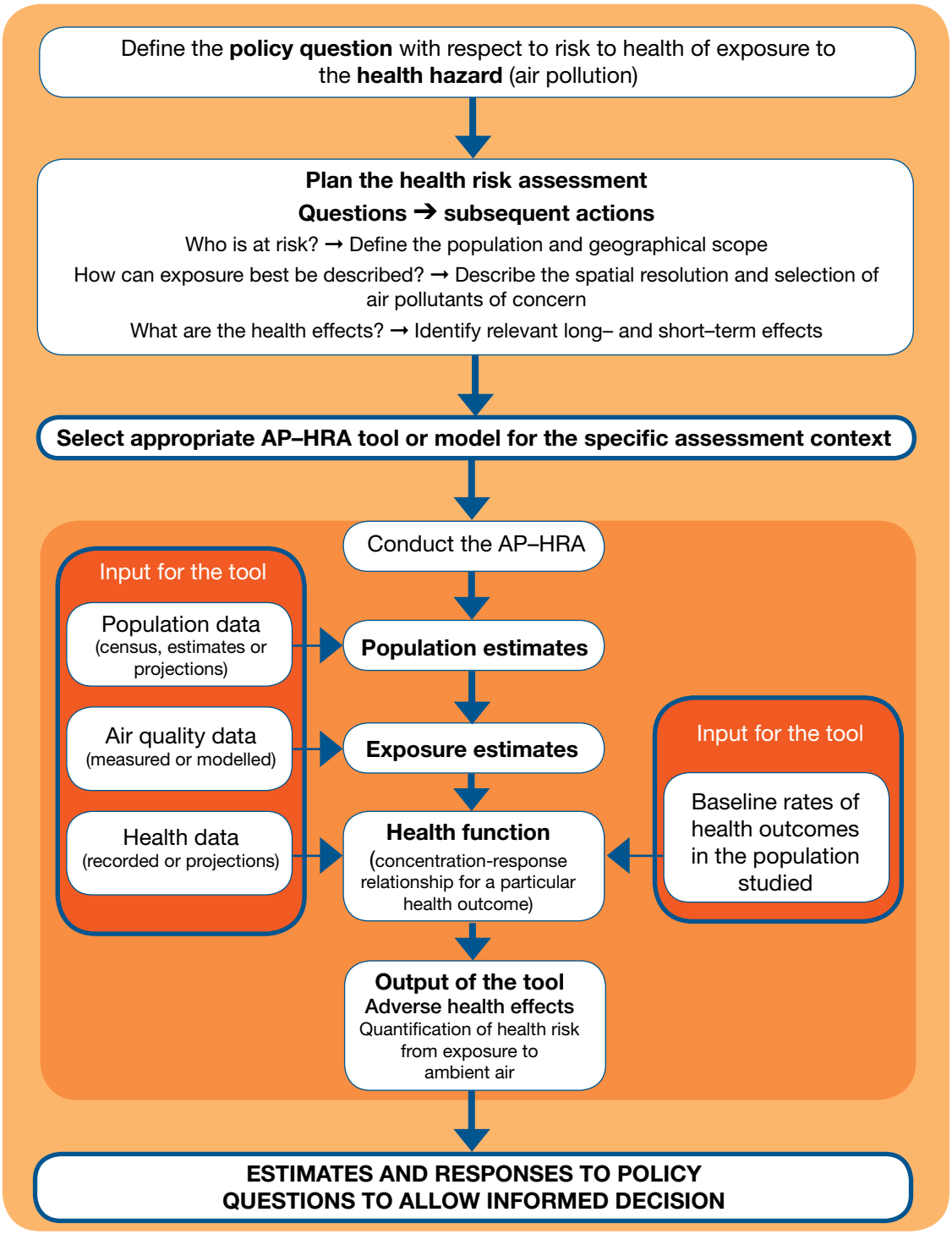
As an analytical tool, an AP-HRA can be used as part of a comprehensive assessment of the health impacts of policies, programmes, and projects that affect environmental conditions – a health impact assessment (HIA). AP-HRA and HIA are different concepts, although the two terms are sometimes used interchangeably. An HIA may be defined as follows (WHO Regional Office for Europe, 1999): “a combination of procedures, methods and tools by which a policy, programme or project may be judged as to its potential effects on the health of a population, and the distribution of those effects within the population.” An HIA identifies appropriate actions to manage those effects (Quigley et al., 2006).

While an HRA tends to look into particular hazards and their effects on human health, an HIA takes a broader perspective. For example, when planning the construction of a new industrial site in or near a city, an HIA would look into not only the specific risks associated with possible air pollutants, but also

issues such as noise and soil and water pollution, as well as the potential impact on the population of the city through, for example, the influx of construction workers, employment opportunities for inhabitants of the city, and the possible accumulation of hazards with already existing hazards in the area.

The focus of this publication is on AP-HRA considering the definitions provided above. An overview of the steps involved in an AP-HRA is given in Figure 3.

Figure 3. Overview of an AP-HRA process (Quigley et al., 2006; US EPA, 2012; WHO Regional Office for Europe, 2014a)



2. Definition of the policy question

As outlined above, the main purpose of an AP-HRA is to answer policy questions about the likely health impacts of planned policies or modifications of air quality.

AP-HRAs are often used to answer the following policy questions (WHO Regional Office for Europe, 2014).

1. What is the public health burden associated with current levels of air pollution?
2. What are the human health benefits associated with changing an air quality policy or applying a more stringent air quality standard?
3. What are the human health impacts of emissions from specific sources or selected economic sectors, and what are the benefits of policies related to them?
4. What are the human health impacts of current policy or implemented action?
5. What are the policy implications of the uncertainties of the assessment?

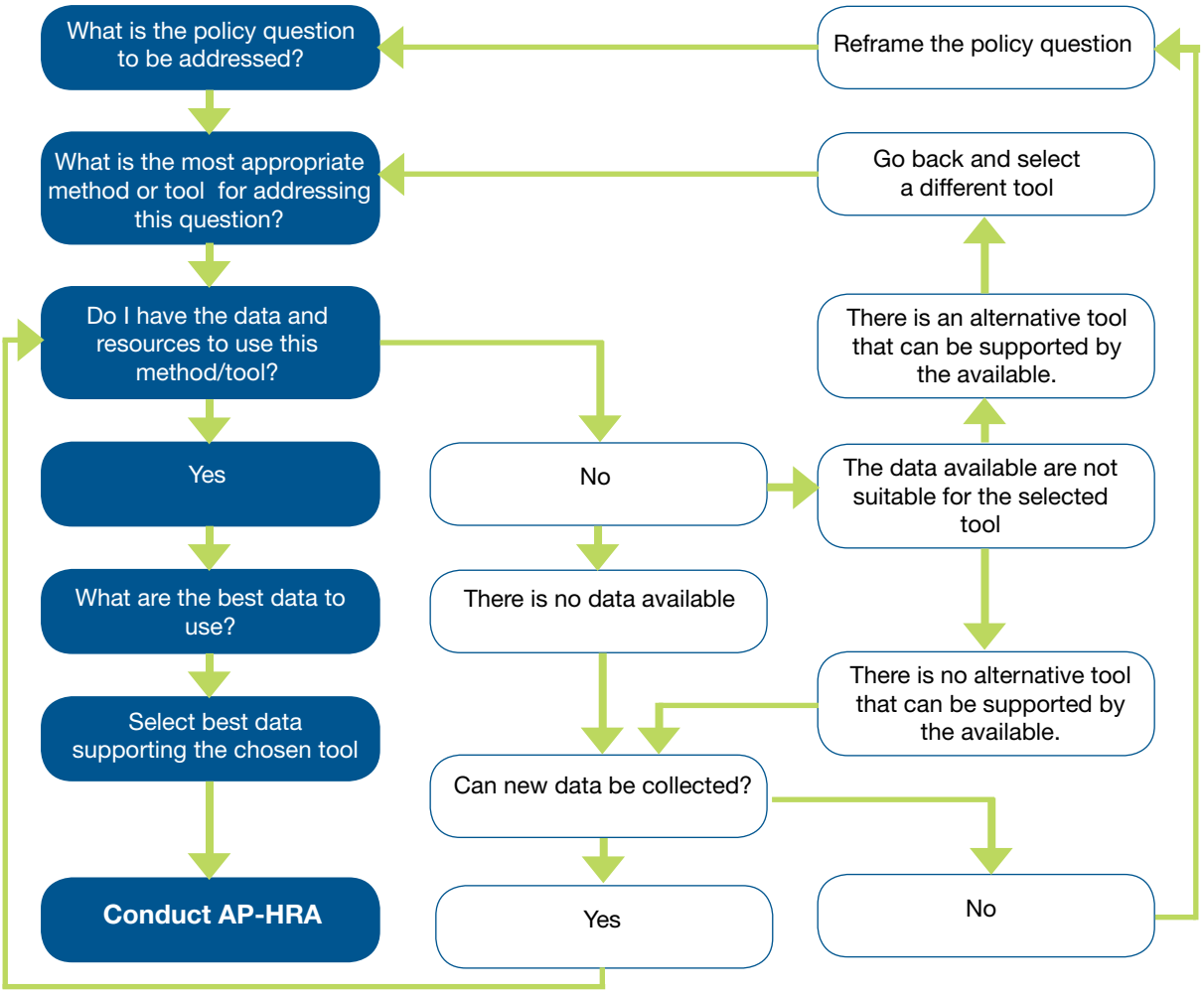
The results of an AP-HRA can be used in an estimation of the economic value of health benefits resulting from a change in policy. Some AP-HRA tools incorporate this step. The knowledge gained through an AP-HRA can also be used to improve policies, such as increasing the stringency of air quality standards.

3. What information is needed to conduct an AP-HRA?

3.1 Planning the health risk assessment

Figure 4 shows a schematic decision-tree for an AP-HRA process, covering definition of the policy question, determination of the availability of data and resources, and selection of appropriate methods and tools. Input data are required on, for example: (1) the level of air pollution, (2) the exposed population, and (3) the health outcome affected (concentration–response functions). The selection of the method may depend on data availability or may determine the data requirements. In addition, different tools will entail different workloads and require different levels of expertise. A detailed overview of the various tools available is presented in section 5.

Figure 4. Decision-tree showing the sequence of choices and feedback loops when conducting an AP-HRA



The following factors should be considered with respect to data needs and availability, depending on the question to be answered (WHO Regional Office for Europe, 2014).

1) The policy question and the event or condition of interest will define the data needs with respect to the following.

- Who is affected? For example, is there a need to consider specific subpopulations in the targeted population, such as certain age groups (children, elderly), people susceptible to specific diseases, particular occupational or socioeconomic groups?
- How are people affected by air pollution? What health outcome will be assessed in the AP-HRA, e.g. mortality, hospital admissions, incidence rate of a specific disease or work loss?
- Which key pollutant indicators are to be considered to describe the exposure and estimate the health risk for a specific population in a specific situation? This will depend on whether the policy question is concerned with, for example, air pollution emissions from specific sources, the effect of the implementation of specific legislation or air quality in general. If measured air quality data are used, what type of measurement data is needed, e.g. urban background levels, traffic emissions or stationary industrial measurements?
- What is the spatial resolution of the issue or question to be assessed in the AP-HRA: one specific city, specific locations within a city, multiple cities, a region, the whole country or an even broader area?
- What is the temporal resolution of the issue or question to be assessed in the AP-HRA: specific decades, years, seasons or days; the period before, during or after a specific event; or a comparison of historical data with future projections?

2) The selection of the tool will define the data needs with respect to the following.

- What spatial resolution of the air pollution and population data is needed? Will census data be needed for a city, a specific location in a city, a specific region or the country as a whole?
- What temporal resolution of the air pollution data is needed: hourly, daily or annual averages?
- What temporal resolution of the health data is needed? Is there a need, for example, for daily number of incidents or hospital admissions, daily mortality or annual mortality?
- Are the data needed for the AP-HRA available? Is there a database that meets the data needs, such as baseline public health and population data?
    - Are measurements of air pollution available, or modelled data? Are tools available to model relevant exposure data in a temporal and spatial resolution that allows the exposure of the affected population to be described? Are the data of adequate quality, were proper monitoring protocols used and did they undergo a quality assurance or control process?
- Have there been previous studies describing the concentration–response relationship for the health outcomes of interest?
- How many people in the population of interest are affected by a specific health outcome caused by air pollution? What are the baseline statistics for the health outcome, i.e. how much of the observed adverse health effect or change in a specific health outcome can be assigned to air pollution or to changes in air quality? Are there data on a control area or control population that can be used for comparison?

3) **Once the desired data have been identified, the availability of the data has to be assessed.**

   If all the desired data are available, it is possible to proceed to the next step. Otherwise either more data will have to be gathered, a different tool will have to be selected or a different policy question will have to be asked.

4) **The available, compiled data on exposure to air pollution, health and population are then used to assess the health impacts associated with exposure to air pollutants with respect to the specific policy question to be answered.**

   This involves the following steps.

   a. Estimate the exposure for the assessed population.

   b. Use the exposure estimates and baseline health outcome rates as input data for a function describing the concentration–response relationship. This will allow the health risk associated with the estimated exposure to be assessed for the population.

   c. As an optional additional step, an economic evaluation to quantify the monetary cost or benefits of the health impacts may be conducted. Some AP-HRA tools incorporate this step.

3.2 Estimating population exposure to air pollutants

Data on population exposure to air pollutants generally come from monitoring by local or national institutions. Estimations of population exposure based on measured air pollution data are often limited by the restricted geographical and time coverage. In addition, it may be difficult to reconcile data from different locations since measurements are often made using different procedures and techniques (WHO Regional Office for Europe, 2014). Even the methods used in one location may change with time. Recent progress in combining satellite remote sensing, global chemical transport modelling, land use regression models and high-resolution local dispersion models in combination with existing ground-based monitoring has made information on key air pollutant indicators increasingly available, including in some of the most highly polluted and data-poor regions (Brauer et al., 2012; Hoek et al., 2008; Paciorek & Liu, 2012; UNECE, 2010; van Donkelaar et al., 2010).

When estimating the change in population exposure as a result of a hypothetical change in emissions or pollutant concentrations, monitoring data may be used as a baseline level. Air quality modelling is, however, needed to estimate future concentration changes resulting from policies and technological innovations.

3.3 Estimating the health risk

The risk of air pollution to health in a population is usually represented by a concentration–response function, which is typically based on Relative Risk (RR) estimates derived from epidemiological studies. The RR estimate describes the likelihood of an adverse health outcome (e.g. premature death, heart attack, asthma attack, emergency room visit, hospital admission) occurring in a population exposed to a higher level of air pollution relative to that in a population with a lower exposure level. Typically, RR is expressed as the proportional increase in the assessed health outcome associated with a given increase in pollutant concentrations in μg per m^3 or parts per billion (ppb) (Katsouyanni,

2003). It is important to note that the RR estimate cannot be assigned to a specific person; it describes risk in a defined population, not individual risk (Australian Department of Health, 2012; McAuley & Hrudey, 2006).

In order to provide useful advice aimed at answering a specific question, the AP-HRA assesses a specific health endpoint or set of health endpoints in a specific population. The analysis does not cover the full range of possible adverse health effects in all possible groups of the population.

The CRFs used in AP-HRA tools are typically based on the epidemiological evidence available for a specific health outcome. Some are based on evidence from experiments in which people or animals are deliberately exposed to a pollutant (WHO Regional Office for Europe, 2014). The CRF may therefore be refined as new scientific evidence becomes available. For some specific health endpoints or air pollutants, the available data may be limited or old and no longer considered appropriate, so that it may not be possible to describe the concentration–response relationship. For example, the likely health risks of exposure to ultrafine particles are currently not considered, as there is no reliable CRF available (Hoek et al., 2010). In some cases, CRFs available may not be appropriate for very high and very low concentrations. Finally, it is important to note that most studies have been carried out in Europe and North America. Pollution levels, chemical composition and health care systems may be very different in other places, and this may affect the CRF.

All these factors mean that, in certain assessment contexts, the absence of direct epidemiological evidence about the health risk of exposure to air pollution is an important limitation. In some of the most highly polluted regions of the world, there is a severe lack of direct epidemiological evidence. Studies are urgently needed in these areas, because the health response per unit change in air pollution at such high levels may differ from that seen in countries with lower pollution levels. For regions with limited or no epidemiological evidence, information from studies in other parts of the world may be used to conduct an AP-HRA. However, such extrapolated information may not accurately describe the concentration–response relationship in the region to be assessed, leading to uncertainties in the results (see section 4.1) (WHO Regional Office for Europe, 2014).

Some tools allow the user to select the CRFs to be applied to the specific assessment, whereas in other cases the recommended CRFs are directly embedded in the tool.

When generating and communicating AP-HRA results for a specific health endpoint, it should be kept in mind that the effects of long-term exposure are much greater than those observed for short-term exposure (WHO Regional Office for Europe, 2013).

3.4 Quantifying the health impact

Results of AP-HRAs are often reported in terms of number of the attributable deaths or cases of disease, years of life lost (YLL), disability-adjusted life years (DALYs), or change in life expectancy attributable to total exposure to air pollution or a change in exposure (WHO Regional Office for Europe, 2014)). These metrics aggregate different types of health impact and can be used to highlight different aspects of the health status of a population (Murray & Lopez, 2013). It is important to note that these metrics provide expected values for a whole population and cannot be applied to individuals in that population.

Number of attributable deaths or cases of disease. This is calculated as the difference in number of deaths or cases of diseases between the incidence/rate at the exposure measured

over a specific period and that at baseline exposure, e.g. difference between current disease incidence and historical incidence or projected future incidence, or total health risk (in relation to zero exposure or to some assumed threshold value) (WHO Regional Office for Europe, 2014).

Years of life lost. YLL is a measure of the years of life lost as a result of premature death. In simplified terms, the calculated number of deaths attributable to changes in exposure to air pollution is multiplied by the standard life expectancy at the age at which death occurs. In some cases, social value weights are also applied (WHO, 2014). Social value weights include disability weights (used in the calculation of YLD (see below)), time discounting and age weights, which assign different values to the time lived at different ages, to reflect varying societal roles and changing levels of dependence with age (Murray, 1994; WHO, 2014). Discounting takes into account whether a year of healthy life gained now is worth more to society than one gained sometime in the future, while age weighting reflects the fact that lost years of healthy life are valued more at some ages than others (Murray & Acharya, 1997; SA Health, 2003). An example of a study that applied social value weights is the Global Burden of Disease Study.

Years lost due to disability. YLD measures years lost due to disability. It is estimated by multiplying the number of incident cases of a particular health outcome in a particular period by the average duration of the case until remission or death (years) and a disability weight factor that reflects the severity of the disease on a scale from 0 (perfect health) to 1 (dead) (WHO, 2014). The GBD 2010 study used an updated life expectancy standard for the calculation of YLL and based the YLD calculation on prevalence rather than incidence (WHO 2014). The Prevalence YLD were estimated by multiplying the number of prevalent cases by the disability weight factor.

Disability-adjusted life years. One DALY is one lost year of healthy life. The sum of DALYs across a population – the burden of disease – can be thought of as a measurement of the gap between actual health status and an ideal situation in which the entire population lives to an advanced age, free of disease and disability. Total DALYs for a particular disease or health condition in a population are calculated as the sum of YLL and YLD (WHO, 2014; Murray & Lopez, 2013).

These estimates of impacts can be used for further estimation of the monetary costs and benefits in a health benefits analysis. Some AP-HRA tools incorporate this economic valuation step or it is conducted in a separate step after the AP-HRA. This health benefits analysis yields the economic value of the change in health impacts. If it is a positive change, then it is considered a benefit. If it is negative, it could be considered a cost. This economic valuation is not considering the implementation costs of the policy.

4. Uncertainty in AP-HRA

The uncertainty of an assessment is related to a lack of knowledge about one or more components of the assessment (US EPA, 2011). Uncertainty analysis is an instrumental part of any scientific analysis, and is usually limited to components that are already identified as uncertain ("known unknowns").

It is a challenging yet important task to find a balance between the complexity of information and tools used and the need to produce understandable results for policy-makers and others who do not necessarily have a technical background or expertise in the field (WHO Regional Office for Europe, 2014).

The key sources of uncertainty in an AP-HRA are listed below (WHO Regional Office for Europe, 2014).

1. Air pollutants exist as a complex mixture

Despite great improvements in the science underlying AP-HRAs, it is still not possible to know with complete certainty the effects of air pollution on health (WHO Regional Office for Europe, 2014). There is a considerable body of evidence from epidemiological studies in various parts of the world documenting a wide range of adverse health effects associated with ambient air pollution. However, the observed adverse effects attributed to an individual air pollutant may actually be (partly) attributable to other pollutants in the mixture which are correlated with the assessed pollutant (WHO Regional Office for Europe, 2013). The resulting uncertainty in the outcome of the AP-HRA may be considered "unknown unknowns" and is not included in this document.

2. Baseline disease burden

The number of deaths or cases of disease may be uncertain for a variety of reasons, especially when data from a number of countries are combined. In addition, uncertainty arises when projections are made of population size and deaths in the future.

3. Pollution exposure level

Because there is no full geographical coverage of ground monitors, most AP-HRAs rely to some extent on modelling to estimate exposure. Modelling is also needed for estimates of future exposure based on predicted changes in air pollution as a result of new policies or technological improvements. Since air quality models are based on a set of assumptions, it is not possible to be certain that the estimated exposure coincides with the actual ambient concentrations in a given location. Even if there could be full coverage by ground monitors, all AP-HRAs assume that either measurements made at a specific location or model estimates of average exposure over a particular area are representative of the exposure of the targeted population. Even if population exposure is well estimated, individual exposures can vary substantially, as a result of differences in concentrations at different places as well as individuals' own activity patterns. Personal monitoring is generally necessary to assess individual-level risks.

4. The concentration–response function

CRFs are derived from epidemiological studies, in which assumptions made during the analysis inevitably introduce some uncertainty into the results. In addition, epidemiological evidence on air pollution is scarce or absent in some parts of the world. Most epidemiological studies have been conducted in developed countries, and the range of exposures studied does not necessarily represent what is observed around the world.

For many public health and policy decisions, the mortality attributable to ambient air pollution has to be considered in the context of mortality due to other factors. A comparative risk assessment (CRA) is a type of AP-HRA that provides comparable estimates for the various risk factors; it requires that consistent approaches are used to estimate the various risks (WHO Regional Office for Europe, 2014). The GBD 2010 project, coordinated by the Institute for Health Metrics and Evaluation (IHME), carried out a CRA to compare the burden of disease from various risk factors, including air pollution (Lim et al., 2013). The project developed integrated exposure–response (IER) functions that combined evidence from studies of ambient air pollution, second-hand smoke, household air pollution and active smoking to estimate risk from ambient air pollution over the entire range of exposure (Lim et al., 2013; WHO Regional Office for Europe, 2014).

5. The counterfactual level of air pollution

The counterfactual level of air pollution is a baseline or reference exposure against which the health impacts of air pollution are calculated (WHO, 2014b). This level of air pollution may be defined differently in different AP-HRAs, depending on the policy question to be answered. It may, for example, be defined as the national air quality standard, the WHO air quality guideline (AQG) level, the natural level (i.e. without anthropogenic influence) or the lowest level observed in epidemiological studies (WHO Regional Office for Europe, 2014). Uncertainty in the counterfactual level may be due to imperfect knowledge about the exact effect of some previous policy change or a theoretical minimum level of pollution (WHO Regional Office for Europe, 2014). It should be noted that choosing a counterfactual level of air pollution is not an uncertainty in the same sense as those previously discussed. The results of the AP-HRA are sensitive to this choice, but they are not themselves made uncertain by it.

6. Deliberate simplifications of the model

Practical considerations may require the use of a simplified model, which can lead to increased uncertainty (WHO, 2005).

It is important that these various sources of uncertainty are acknowledged and described as fully as possible, to give a sense of the precision of the estimates. Uncertainties arise mainly from the current understanding of CRFs and from exposure estimates. In addition, there are probably components of uncertainty that are not recognized. Despite these uncertainties, an AP-HRA can provide useful and valid results. Therefore, while it is important to communicate uncertainties, the message should be balanced to ensure that decision-makers take the results of the AP-HRA seriously. The multiple sources of uncertainty may be quantified by Monte Carlo simulations or probabilistic simulations, as was done in the GBD 2010 study (Lim et al., 2013).

Confidence in AP-HRA estimates

The results of the uncertainty analysis are usually presented as ranges, with the focus being on confidence intervals around the mean (WHO Regional Office for Europe, 2014). Conventionally, 95% confidence intervals are used to provide an estimate of the precision of the results. This interval is the range of values within which there is a 95% probability that the true value lies (Scott, 2008; US EPA, 2015).

For example, as outlined in Annex 3, the uncertainty in the estimates in the GBD 2010 study (Lim et al., 2013) was presented as numerical ranges, i.e. confidence intervals around the mean.

5. Tools available

Computer-based tools are now available that automate the process of an AP-HRA. These tools offer several advantages to the practitioner and end-user, including simplicity (lowering the barrier to conducting assessments), consistency, comparability among assessments, and quality assurance.

Most tools use similar approaches, relying on epidemiologically derived concentration–response functions and population-level exposure estimates to determine the proportion of cases of a particular health effect that may be attributable to a change in air quality. Automated tools are typically preloaded with health and demographic data and concentration-response functions, and some allow for user-specified inputs. However, the tools vary in many aspects, and analysts should choose the one that most closely matches the context of the assessment.

In preparation for a WHO Expert Meeting in May 2014, health risk assessment tools were surveyed to ascertain their technical and operational characteristics. Information was collected on 12 air pollution health risk assessment tools (Table 1). Detailed tables of tool

Table 1. Air pollution health impact assessment tools

Tool	Developing institution	Geographical scope	Health endpoint addressed[1]
AirCounts	Abt Associates	Global (42 cities, additional 3000 under development)	Mortality
AirQ2.2 (update under development)	World Health Organization	Any population with specified size, mortality and morbidity characteristics	Mortality and morbidity
Aphekom	French Institute of Public Health Surveillance	Global (current version focuses on Europe)	Mortality and morbidity
Economic Valuation of Air Pollution (EVA)	Aarhus University	Northern hemisphere, continental (e.g. Europe), national, city	Mortality and morbidity
EcoSense	University of Stuttgart	Europe	Mortality and morbidity
Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE)	US Environmental Protection Agency	Continental USA and China pre-defined; any other as defined by user	Mortality and morbidity
Environmental Burden of Disease (EBD) Assessment tool for ambient air pollution	World Health Organization	Global	Mortality and morbidity
GMAPS[2]	World Bank	Global	Mortality and morbidity
IOMLIFET	Institute of Occupational Medicine	Can be used anywhere where there is background mortality data and measured or predicted pollutant concentrations	Mortality and morbidity
Rapid Co-benefits Calculator	US Environmental Protection Agency, Stockholm Environment Institute	Under development for all countries globally	Mortality
SIM-Air	Urban emissions	Asia, Africa, Latin America	Mortality
TM5-FASST	European Commission Joint Research Centre	Global (56 source regions)	Mortality and morbidity

1 Morbidity may include, for example, cardiovascular diseases, respiratory diseases, hospital admissions, emergency room admissions, days of restricted activity, and work loss days. Not all tools address all morbidity outcomes.
2 The model itself is no longer actively maintained and therefore no longer available for download.

characteristics can be found elsewhere (WHO Regional Office for Europe, 2014) and examples provided in Annex. Most of these tools are available without charge.

Often the first factor that must be considered is the tool's geographical scope, or the spatial coverage or extent of the tool as currently configured. Geographical scope is distinct from spatial resolution, which is the degree of granularity allowed by the tool. For example, a tool with global scope may have a national-scale resolution, city-scale resolution, or a gridded resolution.

The characteristics of the available tools should also be considered and matched against the needs of the assessment context to select the most appropriate one for addressing the policy question. The key technical factors of the tools are listed below.

- **Pollutants addressed.** Most tools are preconfigured to assess the effects of PM ($PM_{2.5}$ and PM_{10}) and ozone. Some also include NO_x, sulfur oxides (SO_x), carbon monoxide, heavy metals or black smoke.
- **Health outcomes quantified.** All the tools reviewed assess impact on premature mortality in terms of the number of excess or avoided deaths. Many tools can also quantify the number of life years lost, disability-adjusted life years (healthy life years lost) and cases of disease (e.g. chronic obstructive pulmonary disorder).
- **Resolution.** Some tools assign air quality values to a grid, which divides the geographical scope into cells (either uniform or variable in shape). Population exposure and health impacts are quantified separately for each cell. Other tools assign air quality data to areas within geopolitical boundaries, such as countries, provinces, and cities. Ideally, the spatial resolution of the tool should match the spatial resolution of the assessment context (e.g. a tool with city-level or finer resolution should be used to assess the effects of air pollution in cities).
- **Exposure characterization.** Most tools rely on air quality modelling to estimate exposure, although some may also be able to take observations from air quality monitors. Some of these tools use full air quality modelling, which accounts for the complex atmospheric chemistry and transport governing air pollution and simulates the influence of emission controls on air pollution levels. When air quality modelling is unavailable, reduced-form tools can generate broad-scale estimates of the impact of air pollution from built-in relationships between emissions and the exposure metric (often concentration) derived from externally conducted air quality model simulations. Care must be taken to match the spatial resolution of the assessment context, the air quality model, and the epidemiological inputs to the health impact function as closely as possible.
- **Data sources.** Health impact assessments typically rely on information about population size and characteristics (e.g. age distribution), baseline mortality and disease incidence rates (usually derived from country statistics), and concentration–response functions (usually derived from epidemiological studies). Some tools are flexible enough to allow users to input data from any source. Others are preconfigured with data from specific sources, and users must decide whether those datasets are appropriate for their assessment context.

The available tools also have a range of operational characteristics, and their abilities and constraints, including resources and expertise, should be considered. The key operational characteristics are listed below.

- **Format.** Some tools are client-based software programs, which have to be downloaded and installed by users. These tools include extensive datasets of health impact functions, population, and health data, which may be modified; these tools are generally complicated and users may need to invest time

and resources in learning how to use them. Other tools depend on external software of general application (e.g. Microsoft Excel), which is generally accessible to most users but may need to be purchased. Since many analysts are familiar with Microsoft Office, extra training may not be necessary. A few tools are web-based, allowing users to generate air pollution health impact estimates without downloading or installing a program. Web-based tools may be most accessible to non-technical users, particularly in countries that lack the resources to conduct full-scale, detailed, and refined health impact assessments. Some tools offer online tutorials and training workshops (e.g. BenMAP-CE, IOMLIFET, SIM-Air).

- **Complexity.** The tools described here vary in technical complexity and accessibility. Users will need to find a balance between their ability to deal with technical complexity and the level of specificity called for in the policy context.
- **Degree of peer-review and use in policy settings.** Analysts should consider whether the tool has been peer-reviewed, the extent to which it has been used to inform policy, and whether it is open-source or proprietary. Some tools have been externally peer-reviewed and have been used extensively in support of national air quality regulations (e.g. US EPA National Ambient Air Quality Standards). A critical advantage of open-source tools is that they are fully transparent, allowing analysts to evaluate the underlying algorithms and datasets used to calculate impact (Anenberg et al., 2015).
- **Degree of maintenance.** Analysts should consider whether the tool is maintained as a living tool, with updates of datasets and methods over time, or is fixed. The data inputs required for air pollution health impact assessments should be updated over time to reflect changes in the science.

Table 2 classifies the surveyed tools according to two of the most common considerations when conducting AP-HRAs: (1) the user input required to characterize exposure (pollutant emissions or concentration levels); and (2) spatial resolution (e.g. regional (more than one country), national, or city-level). A third factor that often needs to be considered is the pollutants addressed by the tool. Table 2 thus indicates, on the basis of these three factors, which available tools are appropriate in the context of a given assessment. Analysts would then need to ensure that the other technical and operational characteristics of the tools are consistent with their needs and capabilities.

The use of Table 2 can best be demonstrated through several fictional examples.

1. An international development organization is interested in estimating the health benefits of $PM_{2.5}$ reductions associated with improved public transport systems in cities. It has projections of emission reductions but does not have the resources to simulate the resulting $PM_{2.5}$ concentration changes. Table 2 indicates the tools that can (a) read in emission estimates, (b) have city-level resolution, and (c) quantify $PM_{2.5}$ health impacts: AirCounts, SIM-Air, Aphekom, and EcoSense.
2. An analyst working for an environment ministry in a developed country wants to assess the national health benefits of a power plant emission regulation that is expected to reduce both $PM_{2.5}$ and ozone. She has resources to estimate emissions and simulate concentration changes. Table 2 shows that she can use any of the tools that read in concentrations, except EBD which does not address ozone: BenMAP-CE, AirQ2.2, IOMLIFET, and EVA.
3. An analyst working for an environment ministry in a developing country wants to estimate the national $PM_{2.5}$-related health benefits of adopting new diesel vehicle emission standards, but has no resources to run air quality modelling. The analyst might consider using a

Table 2. Classification of available tools according to user input needed to characterize exposure, spatial resolution and pollutants dealt with

User input needed to characterize exposure[1]	Emissions									Concentration
Spatial resolution	**Regional**			**National**			**City**			**Any**
Pollutant	**$PM_{2.5}$**	**Ozone**	**Other**	**$PM_{2.5}$**	**Ozone**	**Other**	**$PM_{2.5}$**	**Ozone**	**Other**	**Any**
AirCounts	SIM-Air	-	SIM-Air (PM_{10})	Co-benefits Calculator TM5-FASST EcoSense	Co-benefits Calculator TM5-FASST EcoSense	TM5-FASST (NO_x, SO_x) EcoSense (NO_x, SO_x, CO, heavy metals, dioxins, radio-nucleotides)	AirCounts™ SIM-Air Aphekom EcoSense	Aphekom EcoSense	SIM-Air (PM_{10}) EcoSense (NO_x, SO_x, CO, heavy metals, dioxins, radio-nucleotides)	BenMAP-CE AirQ2.2 IOMLIFET EVA EBD (no ozone)

1 Tools that read in emissions datasets are often considered "reduced-form" tools, as they can generate broad-scale estimates of the impact of air pollution from built-in relationships between emissions and the exposure metric (often concentrations) derived from externally conducted air quality model simulations. Tools that read in concentrations require the analyst to generate concentration datasets externally (either from air monitoring or air quality modelling simulations). One tool (GMAPS) reads in economic and climate indicators from a reduced-form econometric model and is not included in this table.

tool that reads in emissions, runs at a national resolution, and quantifies $PM_{2.5}$ health impacts: Co-benefits Calculator, TM5-FASST, or EcoSense.

The various AP-HRA tools have made it easier for analysts to respond to a range of policy questions by conducting different types of assessment in a consistent and reliable manner. While analysts should strive to use the most technically sound methods for conducting assessments (e.g. using air quality modelling to simulate changes in pollutant concentration associated with a certain reduction in emissions), technical refinement often comes at the expense of accessibility (because air quality modelling is technically demanding and resource-intensive). In some cases, using a reduced-form tool that uses emission data to forecast impact may be sufficient. Reduced-form tools use built-in parameterizations, avoiding the need for expensive and resource-intensive chemical transport modelling. For example, a reduced-form tool would be helpful in estimating the health benefits of different approaches to emission reduction in countries where regional air quality modelling is not available. Even where high quality data exist, reduced-form tools can be used to screen a large number of scenarios, to determine which should be evaluated in greater detail. In general, analysts should use the AP-HRA tools that provide the maximum degree of technical rigour within the resources available.

6. Conclusions

The characterization of health risks in a population from ambient air pollution is critical to the development of effective risk management policies and strategies (Samet & Krewski, 2007).

An AP-HRA can quantify the health impact of air pollution or of changes in air pollution resulting from different socioeconomic, environmental, or policy circumstances. In many countries, an AP-HRA is formally required as part of the decision-making process for new programmes, projects, regulations, and policies that may affect air quality. It is, therefore, important for decision-makers to understand why an AP-HRA is instructive, what resources and institutions are needed for AP-HRA, and what the limitations of the assessment may be. Those conducting an AP-HRA need to understand how to do it, know what data are available and needed and where to find them, and how to communicate the results.

Various AP-HRA tools are currently available. When selecting the most appropriate tool for the assessment context, it is important first to define the policy question to be answered and the audiences to be informed. Next, the technical needs of the assessment context need to be identified, such as the relevant pollutants and the geographical scale, to allow the most appropriate tool to be chosen.

It is often simpler to use an already available automated tool than to develop a new model for each assessment; this also improves consistency, comparability among assessments, and quality assurance. The available tools have a range of technical characteristics (e.g. geographical scope, spatial resolution, pollutants addressed, health outcomes quantified, method of characterizing exposure) and operational characteristics (tool format, complexity, degree of peer-review). Users should try to choose the tool that most closely matches the characteristics of the assessment context. In general, users should choose the AP-HRA tool that provides the maximum degree of technical rigour within the resources available. AP-HRA results should be presented together with confidence intervals that take into account the various possible sources of error in the input parameters. It may be difficult to present the AP-HRA results and the associated uncertainty to decision-makers in an efficient way. Communication experts may be able to help ensure more effective communication of the AP-HRA results from the technical experts to policy-makers and other stakeholders.

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Annex 1. Useful AP-HRA resources

AirCounts. http://www.aircounts.com/.

AirQ2.2. http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/activities/ tools-for-health-impact-assessment-of-air-quality-the-airq-2.2-software.

Aphekom. http://www.aphekom.org/web/aphekom.org/publications.

Co-benefits Calculator. *Points of contact: Neal Fann (US Environmental Protection Agency, fann.neal@epa.gov), Harry Vallack (Stockholm Environment Institute, harry.vallack@york.ac.uk).*
To obtain: via the points of contact.

EcoSense. *Point of contact: Joachim Roos (University of Stuttgart, Joachim.Roos@ier.uni-stuttgart.de).*
To obtain: EcoSenseWeb provides a web interface for single source calculations (http://ecosenseweb.ier.uni-stuttgart.de), which can be accessed for a small fee.

Environmental Burden of Disease (EBD) assessment tool for ambient air pollution.
To obtain: contact EBDassessment@who.int.

Economic Valuation of Air Pollution (EVA). T*o obtain: contact Professor Jørgen Brandt (jbr@dmu.dk)*.

GBD. https://www.healthdata.org/gbd.

Global Model of Ambient Particulates (GMAPS). Points of contact: The World Bank, World Development Indicators database. Note: The model itself is no longer actively maintained and therefore no longer available for download.

IOMLIFET. http://www.iom-world.org/research/research-expertise/statistical-services/iomlifet/.

S**IM-Air**. http://www.urbanemissions.info/.

TM5-FASST. *Point of contact: Rita van Dingenen (European Commission Joint Research Centre, rita.vandingenen@jrc.ec.europa.eu).*
How to obtain: via the point of contact.

US EPA BenMAP-CE. http://www.epa.gov/air/benmap.

Ambient air pollution health impact assessment tools with national scope.

Air Quality Benefits Assessment Tool (AQBAT). To obtain: contact Stan Judek (stan.judek@hc-sc.gc.ca).

AP2 (formerly APEEP). https://sites.google.com/site/nickmullershomepage/home/ap2-apeep-model-2.

Co-benefits Risk Assessment (COBRA) screening model. http://epa.gov/statelocalclimate/resources/cobra.html.

Illness Costs of Air Pollution (ICAP). *Points of contact: Canadian Medical Association and Ontario Medical Association websites. Note: The model itself is no longer actively maintained and therefore no longer available for download*.

Integrated Transport and Health Impact Modelling Tool (ITHIM). *Points of contact: James Woodcock (jw745@medschl.cam.ac.uk) and Marko Tainio (mkt27@medschl.cam.ac.uk)*.
To obtain: via the points of contact.

Annex 2. The Aphekom project

The Aphekom project (Chanel et al., 2014; Le Tertre et al., 2014; Medina et al., 2013; Pascal et al., 2013) was a European multicity project that aimed to provide new information and tools to allow: (a) decision-makers to set more effective European, national and local policies on air pollution and health; (b) health professionals to better advise vulnerable individuals on air pollution; and (c) all individuals to better protect their health from the effects of air pollution. Specifically, it aimed to answer the following two questions.

Question 1: What are the health benefits of reducing air pollution to the WHO air quality guideline values in 25 European cities with a total of nearly 39 million inhabitants?

Methods

- Air pollutant assessed: $PM_{2.5}$. An assessment was made of the health benefits that could be obtained if $PM_{2.5}$ concentrations were lowered to meet the WHO air quality guideline value of 10 µg per m^3 (the counterfactual level), with all other variables staying constant.
- Geographical scope: 25 EU cities.
- Population data spatial resolution: City level.

Tools

- Aphekom HIA guidelines and tools (available at: http://www.aphekom.org/web/aphekom.org/publications).

How was population exposure estimated?

From urban background monitoring data averaged across each individual city. The study period 2004–2006 for baseline scenario; monitoring data adjusted to reflect hypothetical air quality policies.

How was the health risk estimated?

From available concentration response functions in the literature for non-accidental, all-cause mortality from $PM_{2.5}$ exposure.

Results

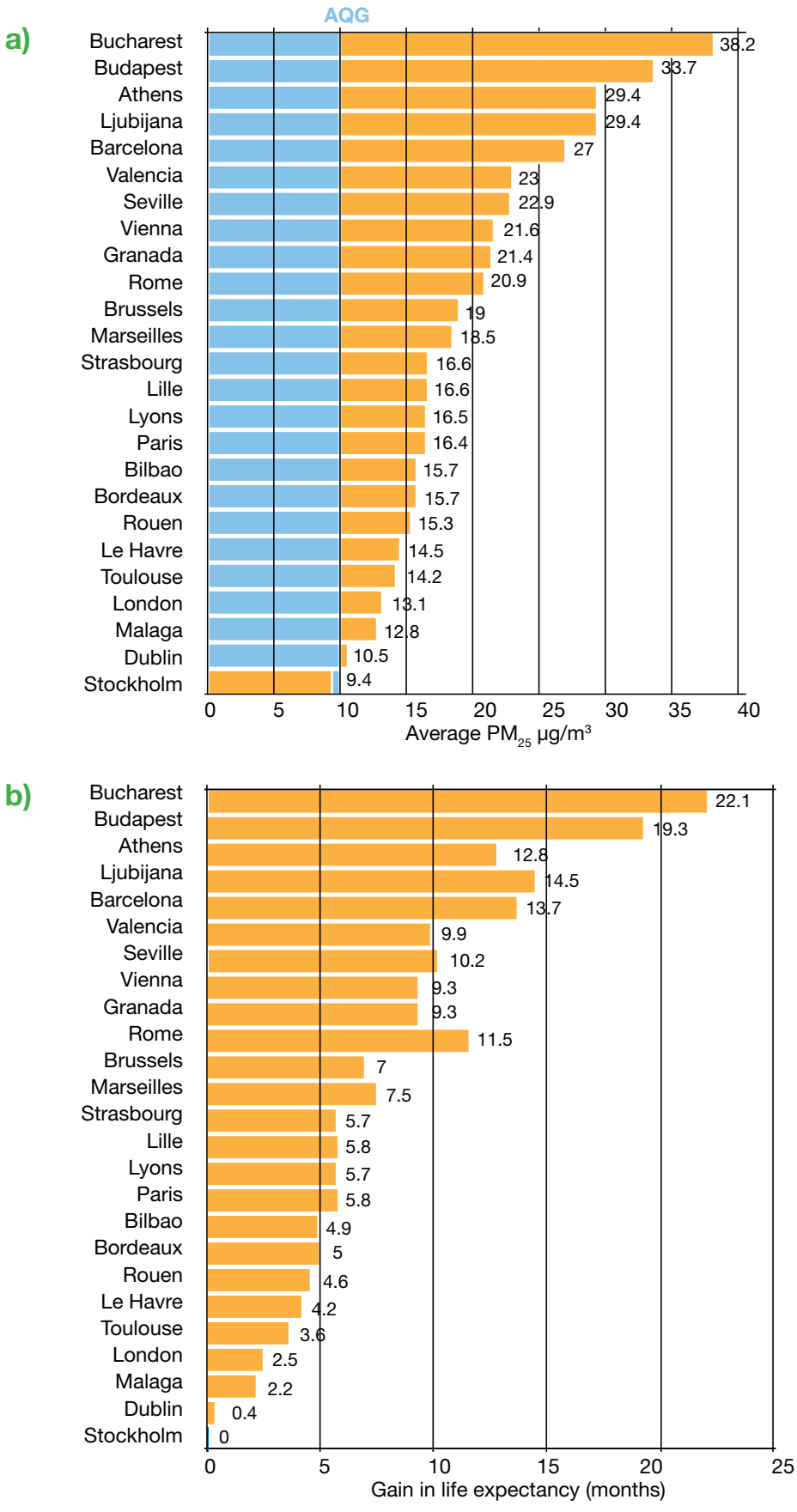
A decrease in annual mean $PM_{2.5}$ level to 10 µg per m^3 could add more than 6 months of life expectancy at age 30 in half of the EU cities (Figure 5). Exceeding the WHO guideline level on $PM_{2.5}$ leads to a burden on mortality of nearly 19 000 deaths per year. The associated costs would reach €30 billion annually (Pascal et al., 2013).

How was the uncertainty of the results treated?

Uncertainties in the CRF and the economic valuation were combined in two different ways. Monte Carlo simulations were done to analyse the uncertainty in the HIA results and the economic values.

Figure 5. (a) $PM_{2.5}$ levels in 25 EU cities and (b) predicted gain in life expectancy from complying with WHO guideline

Adapted from Aphekom (2011)



Question 2: Did policies designed to reduce the sulfur content in certain liquid fuels improve air quality and subsequently public health in 20 cities in the European Union (EU)?

Methods

- Air pollutant assessed: SO_2. An assessment was made of changes in associations between daily concentrations in SO_2 and daily mortality before and after the implementation of legislative measures regulating the sulfur content in certain fuels.
- Geographical scope: 20 EU cities.
- Population data spatial resolution: City level.

Tools

- Aphekom HIA guidelines and tools (available at: http://www.aphekom.org/web/aphekom.org/publications).

How was population exposure estimated?

From urban background monitoring data averaged across each individual city. The study period is 1990–2008.

How was the health risk estimated?

(1) Poisson regression: City-specific risks of death associated with changes in SO_2 for periods prior to and following the implementation of three EU directives. (2) City-specific risk estimates pooled using meta-regression. (3) HIA: estimation of premature deaths avoided as a result of changes in SO_2 after implementation stages compared with baseline levels; economic evaluation.

Results

Overall outcomes were based on data from 20 collaborating EU cities from 2000 onwards, compared with the period prior to implementation of the directive due to reductions in SO_2 concentrations: 2212 lives were saved each year from all causes (95% CI: 772–3663); annual monetary savings were valued at €191.6 million (Chanel et al., 2014; Le Tertre et al., 2014).

How was the uncertainty of the results treated?

Monte Carlo simulations were done to analyse the uncertainty in the HIA results and the economic values.

Annex 3. Global Burden of Disease

The GBD 2010 project, coordinated by IHME (Lim et al., 2013), was a CRA exercise to compare the burden of disease associated with various risk factors, diseases and injuries. Specifically, for air pollution, it aimed to answer the following two questions .[1]

- What is the risk to health from ambient and household air pollution over the entire global range of exposure?
- What are the impacts on health of recently observed air pollution compared with the health burden of other risk factors?

Methods

- Air pollution was assessed 3 different ways:
  $PM_{2.5}$, a common useful indicator of risk associated with exposure to a mixture of pollutants from diverse sources and in different environments assessing (i) ambient PM pollution, and (ii) household air pollution from solid fuels; and ambient ozone, but in the context of this example the focus is on PM only.
- Geographical scope: global.
- Population data spatial resolution: population surveys and censuses.
- CRA approach: consistent methods were used to estimate attributable burden of disease for a variety of risk factors at global, regional, and national levels and their respective uncertainties.
- Impacts for ambient PM pollution were calculated in relation to a counterfactual level, defined by a uniform distribution with lower and upper bounds at the minimum and 5th percentile of the $PM_{2.5}$ exposure distribution of the American Cancer Society Cancer Prevention II cohort study (5.8 µg per m^3 and 8.8 µg per m^3, respectively) (Burnett et al., 2014; Krewski et al., 2009; Lim et al., 2013).

Tools

- Air pollution: TM5-FASST, satellite-based estimates and the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) emission inventory.
- Health risk: integrated exposure–response (IER) model.

How was population exposure estimated?

- Ambient particulate air pollution data integration: remote sensing estimates and chemical transport model simulations were averaged and calibrated with available measurement data in a single global regression model. The resulting estimates provided full global coverage, reduced biases, high spatial resolution and facilitated estimation of source and source-sector contributions to ambient concentrations.
- Household and ambient air pollution were considered as separate risk factors for the global disease burden; the degree of overlap in exposures from these two risk factors was also considered.

How was the health risk estimated?

- IER functions were developed, combining evidence from studies of ambient air pollution, second-hand

1 This annex highlights certain aspects of the GBD 2010 study that are relevant to the content of this publication. The GBD 2013 data are now available as well (Forouzanfar et al., 2015).

smoke, household air pollution and active smoking (Burnett et al., 2014).

- This was done because existing data covered only small concentration ranges and no exposure-response functions were available from studies outside North America and Europe. Existing exposure-response functions could not be directly applied to countries with high levels of air pollution, e.g. in Asia (Lim et al., 2013).
  IER assumptions: air pollution-attributable mortality is independent of other risk factors.

Results

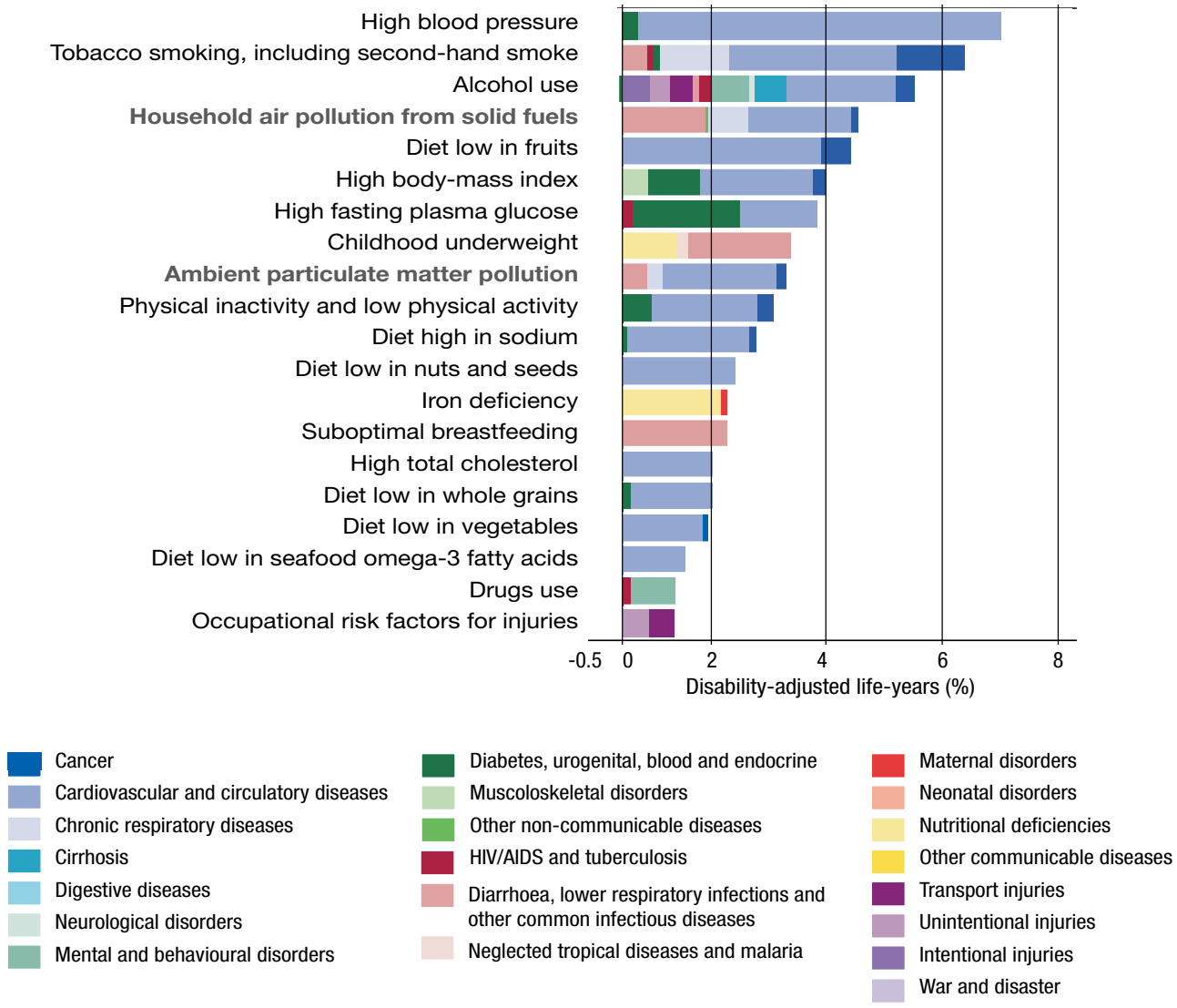
Ambient particulate matter pollution and household air pollution from solid fuels were a significant risk factor for health in 2010, contributing to premature deaths worldwide.

- Household air pollution was ranked as 4th risk factor worldwide for 2010, accounting for 4.5% (3.4–5.3%) of global DALYs (Figure 6) (Lim et al., 2013).
- Ambient air pollution was ranked as 9th risk factor worldwide for 2010, accounting for 3.1% (2.7–3.4%) of global DALYs (Figure 6) (Lim et al., 2013).

How was the uncertainty of the results treated?

The GBD study used simulation methods to incorporate uncertainty from four sources: disease burden, pollution exposure level, response to the pollution, and the counterfactual level of air pollution (WHO Regional Office for Europe, 2014).

Figure 6. Burden of disease attributable to 20 leading risk factors in 2010, expressed as a percentage of global DALYs



Source: reprinted from The Lancet, Vol 380, Lim et al., A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Buren of Disease Study 2010, p. 2244, Elsevier Limited (2013), with permission from Elsevier.

Annex 4. BenMAP

The Environmental Benefits Mapping and Analysis Program (BenMAP) (US EPA, 2014) supports regulatory development in the United States of America. A study was conducted in the USA by the US Environmental Protection Agency (Fann & Risley, 2013) using BenMAP to assess the public health context for $PM_{2.5}$ and ozone air quality trends. The study aimed to answer the following question.

- What is the level of premature mortality incurred or avoided as a result of changes in the level and distribution of $PM_{2.5}$ and O_3 in air nationwide in the USA?

Methods

- Air pollutants assessed: $PM_{2.5}$ and O_3.
- Geographical scope: country.
- Population data spatial resolution: US census block-level populations.
- Approach used involved the estimation of:
  - spatial distribution of changes in ambient air quality resulting from past changes in air quality;
  - change in population exposure, and
  - health impacts (by applying CRFs from the epidemiological literature to the change in population exposure).

Tools

- Air pollution: Voronoi neighbour averaging (VNA) algorithm.
- Population exposure and health risk: BenMAP (US EPA, 2014).

How was population exposure estimated?

- Measured air pollutant monitor concentrations were used to create a 12×12 km gridded spatial map of concentrations for each year from 2000 (the counterfactual level of air pollution) to 2007. Data were interpolated using the VNA algorithm.

How was the health risk estimated?

- Baseline incidence: taken as 3-year average (2006–08) county-level all-cause mortality rates from the CDC-WONDER database.
- Available CRFs: two CRFs were selected for each pollutant, to compensate for strengths and weaknesses inherent in the studies selected, e.g. one may have considered a broader geographical area and the other a larger population.

Results

- Estimated reductions in monitored $PM_{2.5}$ and O_3 concentrations from 2000 to 2007 were associated with an annual total of 22 000–60 000, and 880–4100, avoided premature deaths from all causes, respectively (Figure 7) (Fann & Risley (2013).

How was the uncertainty of the results treated?

- Confidence intervals were estimated using a Monte Carlo analysis.

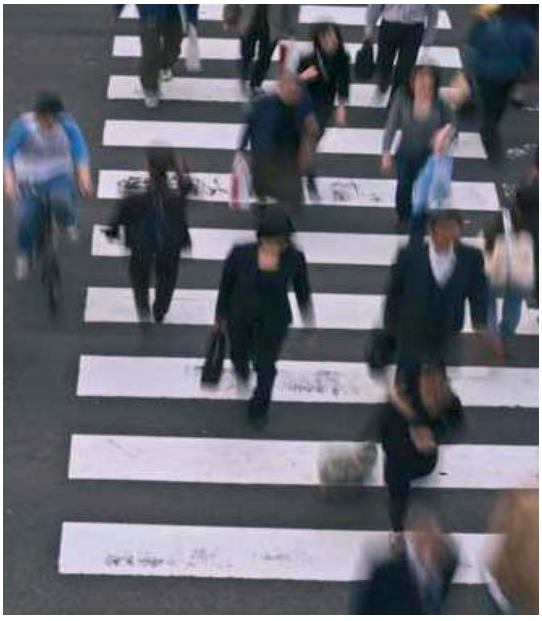
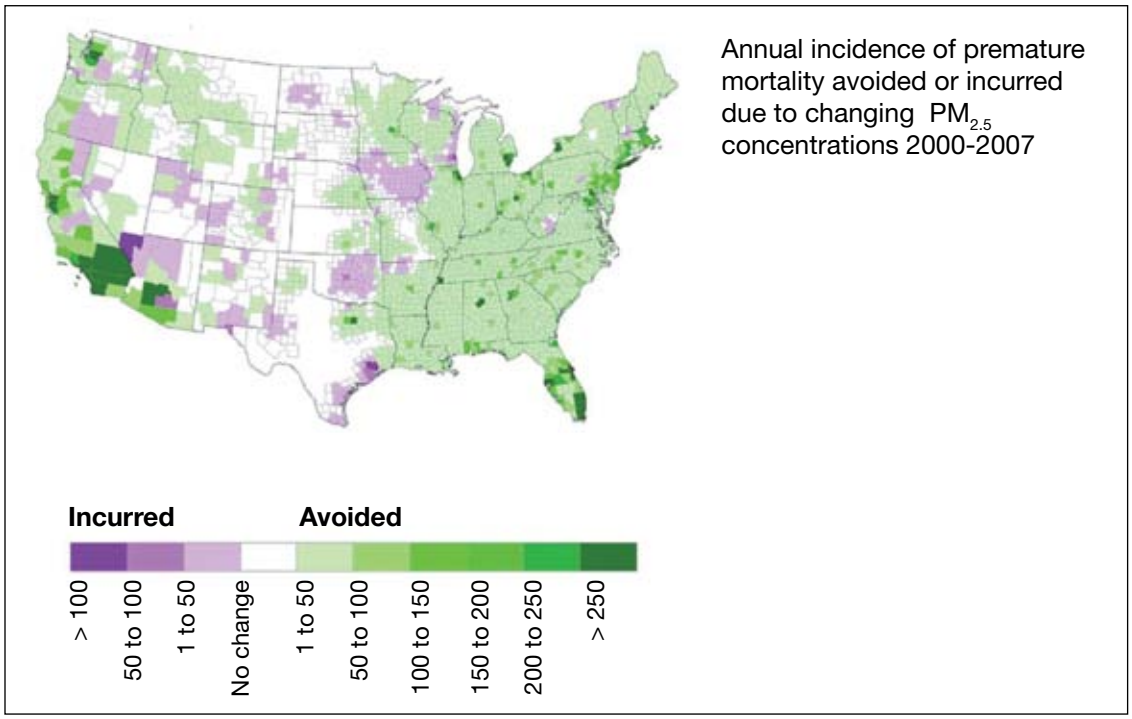
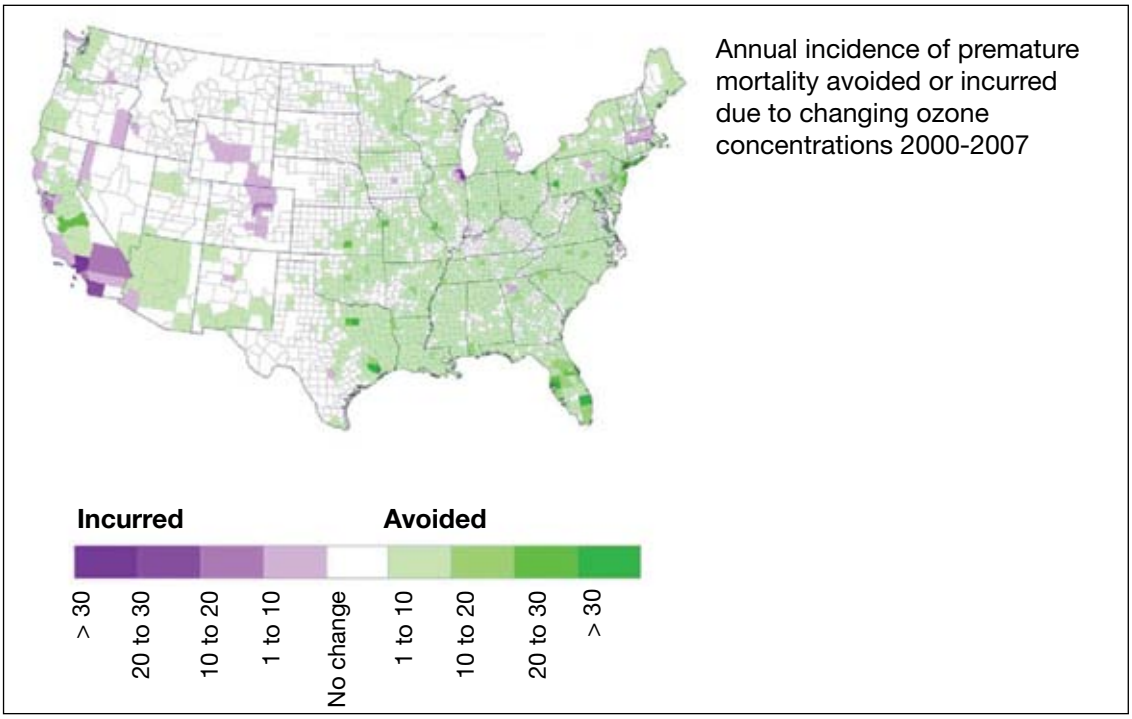


Figure 7. Annual incidence of premature mortality avoided or incurred due to changing $PM_{2.5}$ or ozone concentrations 2000-2007



Annual incidence of premature mortality avoided or incurred due to changing $PM_{2.5}$ concentrations 2000-2007



Annual incidence of premature mortality avoided or incurred due to changing ozone concentrations 2000-2007

Source: Fann & Risley (2013), with kind permission from Springer Science and Business Media.

The WHO Regional Office for Europe

The World Health Organization (WHO) is a specialized agency of the United Nations created in 1948 with the primary responsibility for international health matters and public health. The WHO Regional Office for Europe is one of six regional offices throughout the world, each with its own programme geared to the particular health conditions of the countries it serves.

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