

Chapter 1

Executive Summary

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In 2007, NARSTO was charged with assessing the technical challenges of transitioning from a pollutant-by-pollutant approach to air quality management to the risk-based, multipollutant approach suggested by the U.S. National Research Council in 2004 (NRC 2004). NARSTO's assessment examines current scientific capabilities for achieving a risk-based multipollutant approach to air quality management that also includes a system for assessing the effectiveness of individual air quality management actions; i.e., accountability. The charge to the assessment team was not to provide a roadmap for implementing multipollutant air quality management and accountability but to assess the state of the knowledge and tools for achieving such a management approach and to recommend areas where capabilities and knowledge could be improved. In developing the assessment's conclusions and recommendations, the assessment team considered risk assessment methodologies, atmospheric processes and modeling, measurements and monitoring systems, emissions, climate and other future global-scale changes, and current air quality management initiatives. Although the NRC (2004) recommendations were directed toward the air quality management system in the United States, they are also of great interest to Canada and Mexico as both countries continue to improve the efficiency and effectiveness of their air quality management programs. This assessment does take a North American perspective; however, the authors believe the findings and recommendations should be of interest to other countries as well.

The current frameworks for managing air quality in Canada, the United States, and Mexico (see text box) are well established and generally have been successful in reducing air pollution, especially in urban areas. However, we believe that air quality management can be made more efficient and effective by addressing sources, atmospheric concentrations, exposure, and effects holistically.

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Air Quality Management in North America

Air quality regulations are designed to protect human health, ecosystems, and air-quality related values, such as visibility. The priority in Canada, the United States, and Mexico has been to reduce ambient concentrations of air pollutants that affect large urban portions of North America and pose adverse health consequences for the general population. Following U.S. practice, we refer to these pollutants as criteria pollutants. Traditionally in all three countries, ambient air concentration standards or objectives are set for each criteria pollutant at values that protect the public from adverse health consequences within some adequate margin of safety. The management approach in each country is to specify emission controls, or emission capping or reduction programs, to reduce ambient concentrations while treating each criteria pollutant (or its equivalent) individually. In practice, however, air quality managers do consider physical and chemical interactions among pollutants and how actions taken to address one pollutant might affect others, especially with respect to secondary pollutants like ozone or fine particles.

In addition to the criteria pollutants, certain air pollutants pose concerns because of their specific toxicity or cancer-causing potential. Emissions of these pollutants, called air toxics or hazardous air pollutants, are generally much smaller than those of criteria pollutants, although some sources emit both hazardous and criteria air pollutants. Hazardous air pollutants are regulated (primarily in Canada and the United States) through emission standards or other actions designed to limit individual (as opposed to population) risk. Hazardous air pollutants can also be formed via chemical reactions in polluted atmospheres, and atmospheric processes affect them in ways similar to criteria pollutants. Hazardous air pollutants formed through chemical reactions in the atmosphere have not been a specific focus of air quality standards or management actions.

In addition, air quality management actions can be integrated with measures taken to mitigate anthropogenic contributions to climate change. This latter point is important because common air pollutants (e.g., carbon monoxide, nitrogen oxides, ozone, and particulate matter) can affect the climate; climate change can affect air quality-related emissions and conditions conducive to the formation of air pollution; and policies adopted to reduce emissions important to one problem (air pollution or climate change) can have consequences for the other.

1.1 Features of Risk- and Results-Based Multipollutant Air Quality Management

A risk- and results-based multipollutant air quality management approach has the following features:

- *Administrative Coordination:* All air pollutants and climate-forcing agents are considered together. Reviews of air quality standards are coordinated and placed on compatible schedules. Plans for achieving the standards or desired emission reductions (and analyses of the consequences of these reductions) are coordinated and placed on a common timeline.
- *Risk-Based Decision Making:* When multiple pollutants are controlled simultaneously, the likelihood is even greater that there will be complex changes in exposures to humans and inputs to ecosystems. Thus, air quality management actions should address the greatest integrated risks to human health, ecosystems, and public welfare rather than achieving each ambient standard simultaneously.
- *Accountability:* Results-based multipollutant air quality management includes a formal procedure for assessing progress in implementing air quality management actions, evaluating the effectiveness of these actions in achieving the desired goals, and demonstrating the value of these actions in protecting human health and ecosystems. Accountability goes beyond simple compliance monitoring. In its fullest expression, its goal is to determine whether the action in question is achieving predicted reductions in risks to human and ecosystem health, and if not, why.

1.2 Risk Assessment and Accountability in a Multipollutant Air Quality Management Environment

Figure 1.1 depicts how risk assessment and accountability are linked in a risk- and results-based air quality management environment. Risk assessment is already a part of the air quality management framework in North America. Estimates of risk are employed, to some degree, in setting standards and in designing air quality management actions for meeting these standards. Estimates of risk are derived from the sequence of identifying health and ecological hazards, defining human and ecosystem exposures, and merging hazard and exposure into qualitative and quantitative characterizations of risk.

Risk characterization (the blue-bordered boxes in Fig. 1.1) is an assessment of whether a particular substance has the potential to cause harm to public health or to the environment, and it is a key step in the risk assessment process. Exposure assessment is critical to risk characterization; exposure assessment uses emission inventories, measurements, and emission-based air quality modeling to estimate ambient concentrations of hazardous substances. These concentrations are then used as a surrogate for personal exposure, or they are coupled with human time and activity modeling and other information needed to establish micro-environmental concentrations to estimate personal exposure. Exposure estimates and available concentration-response or exposure-response information then support an estimate of the health or environmental impacts of the substance in question.

If a substance is identified as posing a significant risk, it may be subject to an air quality management action, as indicated by the steps bordered in red in Fig. 1.1.

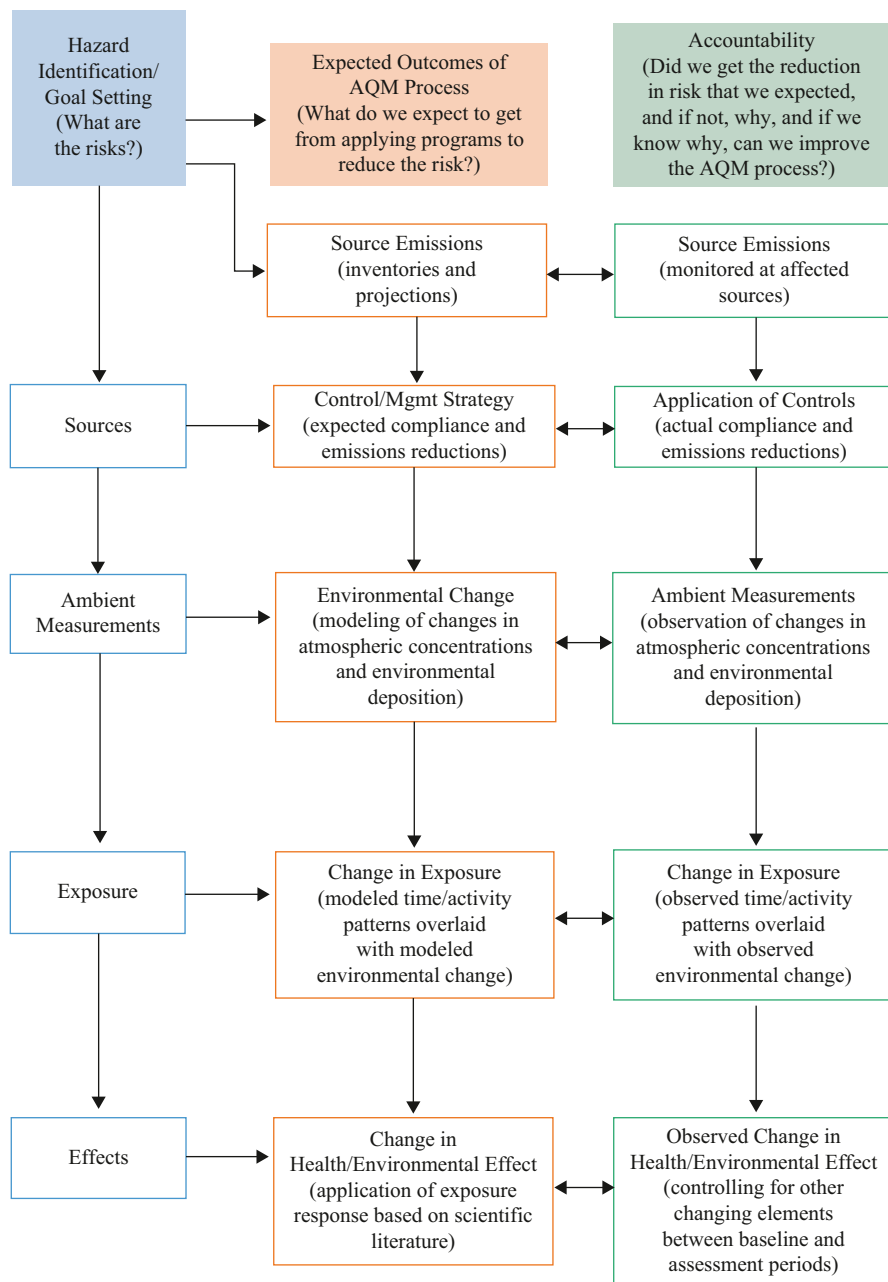


Fig. 1.1 The roles of risk analysis and performance evaluation (accountability) in air quality management practice

As depicted in the figure, development of an air quality management action includes prospective analysis for determining the reductions in emissions, ambient concentrations, and exposure that may be needed to reduce the risk to a desired level of protection. This analysis is based on empirical concentration-response or exposure-response evidence that provides guidance on the ambient concentrations or other indicators of exposure that will achieve the desired level of risk reduction. In the case of ecosystem protection (e.g., protecting forests, agricultural resources, watersheds, and biota from adverse effects of pollutant exposure) or in the assessment of risks associated with hazardous air pollutants, the risk assessment process includes similar exposure and effects assessment in preparing appropriate management decisions.

Risk assessment is used in single pollutant air quality management, but it has not typically been used to assess *relative* risk across pollutants. Under a fully realized multipollutant air quality management regime, however, assessment of relative risk becomes essential. Here, decisions need to be made with regard to multiple pollutants involving multiple sources based on the proposed air quality actions that result in the greatest, or most effective, reduction in the risk of adverse health or ecosystem effects. Decisions may hinge, therefore, on our ability to determine relative risks due to exposure to multiple pollutants, assessed separately, or the risks of exposure to mixtures of pollutants. Decisions may also vary between and within airsheds. For example, mobile sources may present the greatest risk in one airshed, while industrial sources may pose the greatest risk in another. Within an airshed, mobile sources could pose the greatest risk for those living in close proximity to major roadways, while in another part of the airshed other sources (local or regional) could be more significant.

As with risk analysis, performance assessment (or accountability) can be applied in both single pollutant and multipollutant air quality management paradigms. Unlike risk analysis, however, a formal, complete accountability process has not been an integral part of past air quality management programs. As is depicted in the green-bordered boxes in Fig. 1.1, an accountability analysis is implemented through a series of steps sometimes called the accountability chain. These steps determine whether:

1. The management action was implemented as designed and the expected emission reductions have taken place.
2. The actual or estimated emission changes resulted in the expected changes in ambient concentrations or deposition.
3. The changes in ambient concentrations or deposition have resulted in reductions in exposure of humans or ecosystems to the pollutants in question.
4. These reductions have led to improved public health or reduced damage to sensitive ecosystems.

In addition to measuring the effectiveness of air quality management actions, accountability can also be part of a process of continuous improvement. Each step down the accountability chain provides information that can be used to improve the effectiveness or, perhaps, lower the cost of the original air quality management

action. These attributes of accountability—measuring effectiveness and providing corrective feedback—are illustrated by the double-arrow lines in Fig. 1.1.

A major challenge of accountability is that each step down the accountability chain—from emission reductions to health or ecosystem effects—represents an increase in the probative value of the information; however, with each step down the chain it becomes increasingly difficult to establish a clear cause and effect relationship. Emission changes, for example, may result from changes in economic conditions or from the adoption of new technology for reasons unrelated to air quality management. Also, verifying emission changes is not a simple matter for sources not equipped with continuous emission monitoring systems. Likewise, the principal health effects attributed to air pollution (e.g., respiratory stress and heart disease) are also driven by other confounding factors, some of which have much greater impact on one's susceptibility to developing these diseases (e.g., tobacco smoking or changes in health care practices) than ambient air pollution.

The problem of establishing the cause, effect, and benefits of changes in air quality becomes particularly difficult for air quality management actions implemented over a number of years. The longer it takes to implement an air quality management action, the greater the possibility that any observed health or ecosystem outcomes will be affected by confounding factors or that additional actions will have taken place during the same timeframe that complicate the ability to attribute cause and effect.

True accountability goes well beyond the compliance monitoring usually conducted to assess attainment of ambient air quality standards. A complete accountability program that links sources to effects requires advance planning to ensure that the necessary methods and data will be available to provide the level of proof desired. If accountability becomes a formal part of air quality management, planning for accountability demonstrations should be part of any new rule making. The information needed for an accountability demonstration should be tied directly to the risk assessment indicators and process modeling used in the development of the air quality management action in question. One cannot assume that the necessary information will be available post hoc.

1.3 Transitioning to Risk- and Results-Based Multipollutant Air Quality Management

To facilitate thinking about the issues and to organize presentation of the results, the assessment team postulated a four-level transition from pollutant-by-pollutant management to risk-based, accountable, multipollutant air quality management. Accountability can be implemented at each of these levels. At *Levels 1* and *2*, the emphasis is on determining whether the management actions under consideration have achieved the expected reductions in emissions and ambient concentrations or in atmospheric deposition. At *Levels 3* and *4*, accountability extends to determining whether expected reductions in exposure and, ultimately, human health or ecosystem effects are being achieved.

Level 1. A strict single pollutant perspective with the focus on attainment of individual ambient standards.

In current regulatory administrative practice, air quality management actions are developed to meet single pollutant standards without formal consideration of coincident or cumulative benefits or tradeoffs regarding other pollutants. The current underlying information and many of the assessment tools, particularly air quality models, are capable of addressing multiple pollutants; however, these capabilities are only used to assess efficient pathways to attaining a specific ambient standard or objective in a designated area and timeframe.

At *Level 1*, the focus is on attaining the individual standards, and the schedules for developing plans for attaining these standards are not necessarily coordinated. Nevertheless, improvements in emission information, characterization of relevant atmospheric processes, and ambient monitoring are always needed for improving the effectiveness of individual air quality management plans and for demonstrating attainment of the standards. With respect to accountability, consistent emission information should be maintained over a period of years to allow retrospective assessment of trends, and consistent methods for projecting future emissions are needed to project future ambient concentrations and deposition. At *Level 1*, risk assessment is not part of the accountability analysis. Ambient concentration or deposition results from air quality modeling or monitoring networks are handed over to the exposure and effects communities for determining whether or not attainment of the standards is achieving the desired level of human health or ecosystem protection.

Level 2. Attainment of standards for individual pollutants, but with increasing attention to co-benefits attainable through coordinated emission reductions.

At *Level 2*, the focus remains on attaining individual standards, but in a way that considers and optimizes the co-benefits of emission reductions in attaining standards for other pollutants. For example, current air quality models treat a wide range of chemical and physical processes that affect regulated air pollutants such as ozone (and other photochemical oxidants), particulate matter, and certain hazardous air pollutants. Development of air quality management plans for addressing these pollutants and looking for synergistic benefits in reducing emissions from common source-types is quite feasible. In fact, this approach has been explored in the South Coast Air Quality Management District in California and the state of Georgia. Such an approach, for example, might consider the coincident benefits of reducing ambient concentrations of hazardous air pollutants and particulate matter in a strategy designed for ozone reduction, or the coincident ozone reduction benefits of a strategy focused on particulate matter. Such approaches are being considered within the U.S. EPA, and one experimental study has been recently completed in Detroit, Michigan. More detail on these activities, as well as documentation of and support for the conclusions and recommendations provided in this summary, are found in the relevant chapters of this book.

Level 3. Management decisions based on achieving greatest risk reduction based on single pollutant exposure-dose-response relationships.

In contrast to *Levels 1* and *2*, *Level 3* envisions the development and evaluation of emission reduction strategies that simultaneously meet multiple air quality (and deposition) targets or standards without constraining the analysis to meet a single priority target. This approach implies the concept of trade-offs and prioritization of actions based on which actions address the most significant risks or achieve the greatest net reductions in risk, assuming that all risks are additive. This approach requires that target goals (e.g., ambient standards, deposition targets, or benchmark concentrations associated with an agreed-upon risk threshold) be associated with each individual pollutant under consideration, and it requires a formal procedure for conducting risk assessment (including methods for comparative assessment on health risks and ecosystem benefits). Such a formal optimization analysis requires a complex integrated assessment model and appropriately accurate information on the risks associated with the individual single pollutant targets. Such models have been developed, and they could be applied when the appropriate data and evaluation measures are available.

Level 4. Management decisions based on achieving greatest risk reduction based on multipollutant exposure-dose-response models.

Level 4 considers a variety of emission reduction strategies evaluated on the basis of net risk reduction or maximum benefit, taking into account the synergistic effects of exposure to multiple pollutants when such effects exist. This level of multipollutant air quality management assumes the availability of exposure-response functions (and, ideally, evaluation measures) for groups or mixtures of pollutants. By incorporating overall risk reduction, *Level 4* allows for the development and evaluation of comprehensive strategies for the protection of human health and ecosystems. *Level 4* recognizes that the effects of exposure to multiple pollutants range from increases to decreases in the adverse impacts that might be expected by summing individual exposure-response relationships.

1.4 Assessment Conclusions and Recommendations

The purpose of this assessment is to evaluate the technical challenges of implementing a risk-based, results-oriented multipollutant approach to air quality management. The assessment team was asked to evaluate the state of the science now and over the next 5–10 years, and to recommend actions that might be taken to improve it. The assessment follows two threads of thought (1) risk-based multipollutant air quality management and (2) accountability, which is the measurement of results. Multipollutant air quality management could be implemented without accountability, and accountability could be applied to the current, largely single pollutant, air quality management approach. Consequently, we group the conclusions and recommendations of this assessment by those that apply largely to multipollutant air quality management and those that pertain to accountability. In a few cases there may be some overlap.

1.4.1 Multipollutant Air Quality Management

While current air quality regulations generally address single pollutants, most current control strategies address multipollutant interactions; for example, they take into account how actions taken to address one air pollutant (e.g., ozone) may affect another (e.g., $\text{PM}_{2.5}$). Contemporary air quality models can account for ambient chemical interactions among regulated pollutants and estimate how changes in multiple emission sources might affect ambient concentrations for several pollutants simultaneously. *Thus, the basic technical capabilities for developing coordinated emission reduction approaches to controlling air pollution and implementing multipollutant air quality management at Levels 1 and 2 currently exist—as long as sufficiently complete and accurate information on emissions is available and the criterion for success is attaining ambient air quality goals or deposition and emission reduction targets.*

However, the risk-based multipollutant air quality management approach (*Levels 3 or 4*) requires that we have the ability to develop multipollutant management strategies that address “the most significant exposures [and] risks...” and “accomplish comprehensive reductions [in these risks or exposures] in the most cost-effective manner for all priority pollutants” (NRC 2004). In principle, risk analysis frameworks already exist that are suited for analyzing alternative multipollutant management actions. Emission modeling and air quality modeling elements of these frameworks are already multipollutant in character. The principal missing resources are (a) comparable exposure-response information that enables determination of the relative risks of exposure to single and multiple pollutants and (b) improved methods for comparative evaluation of health and ecosystem benefits.

The first step (*Level 3*) in an evolution to a full risk-based multipollutant approach to air quality management is to assess risk on the basis of exposure to multiple individual pollutants. Alternative management strategies can be compared by determining which are most effective in reducing exposure to the pollutant that represented the highest population (or individual) risk or the greatest net benefit assuming all risks were additive. *However, while we have information on the risks of exposure to individual criteria pollutants and some air toxics, this information contains significant uncertainties. These uncertainties include not only those associated with determining exposure, dose, and effect, but also, in some cases, uncertainties in whether the pollutant in question is the actual cause of an adverse effect or a surrogate for that effect. Although our knowledge may be sufficient for setting standards, these uncertainties are currently too great to allow a complete ranking of the severity of risk of exposure to individual pollutants. Partial rankings are feasible where there are large differences in the levels of exposure or toxicity and the agent causing the adverse effect is known unequivocally.*

The next step in implementing a risk-based multipollutant approach to air quality management (*Level 4*) requires an assessment of the effects of simultaneous exposure to multiple air pollutants. *Little is known about the human health and ecosystem effects of exposure to mixtures of pollutants other than to consider co-pollutants*

as confounders of the effects of the principal pollutant under consideration. Therefore, it is unlikely that this level of multipollutant air quality management could be implemented within the next five to ten years. Investigators have had little incentive to sort out the causal components of pollutant mixtures except for studies of the effects of acidification on freshwater ecosystems. Epidemiology has had little power to address potential synergisms, but there is evidence from experimental exposures of humans and animals in laboratory environments that some combinations of pollutants cause greater, and in some cases fewer, than additive effects. Thus, current knowledge indicates that the potential for synergies (or antagonisms) cannot be ignored. With respect to ecosystems, interactions between metals and acidity, as well as combinations of certain persistent organic pollutants, could have adverse synergistic effects in aquatic systems. *If a comprehensive multipollutant approach to air quality management is to be pursued, more attention will need to be given to the consequences and risks of multipollutant exposure. With respect to air toxics and human health, toxicological information could be used for relative risk assessment on the basis of potency (or reactivity) and exposure. However, little of this kind of relative risk assessment has been performed.*

An alternative to moving beyond an approach to air quality management that focuses on attainment of individual ambient air quality standards is to focus on reducing the most significant exposures—those presenting the greatest risks, based on current knowledge, for the greatest number of people. *With improved capabilities for characterizing exposure, air quality management actions could be prioritized according to which might be most effective in reducing exposure of broad population categories to the pollutants or combinations of pollutants presenting the greatest risks as we currently understand them (and setting the stage for future accountability analysis and mid-course correction of management strategies).*

A further advance in multipollutant air quality management might be achieved through grouping approaches in which pollutants such as air toxics are treated collectively on the basis of reactivity, where such characteristics have been linked to a key biological mechanism of harm. Other approaches to dealing with the health effects of pollutant mixtures could also become available in the future. For example, the emerging field of computational toxicology (which involves the integrated application of genomics, proteomics, and advanced computational models) may offer fresh approaches to examining the toxicology of mixtures and assessing their effects.

Lastly, future air quality management in North America could be complicated by three global-scale multipollutant influences:

- Hemispheric transport of long-lived pollutants and pollutant precursors due to increased global emissions, which could affect local and regional air quality management by increasing ambient background concentrations.
- Changes in precursor emissions, within North America as well as globally, that result from actions taken to mitigate anthropogenic climate change.
- Changes in atmospheric chemistry, biogenic emissions, and meteorological conditions brought about by climate change.

In principle, we have the observational and modeling tools needed to assess the effects of hemispheric transport on air quality. Also, modeling simulations indicate that climate change will not radically change our general approach to mitigating poor air quality, although climate change could affect the frequency and intensity of poor air quality episodes and increase the challenge of meeting air quality management goals. Perhaps the most dramatic effect of climate change on air quality, at least in the medium to longer term, could be the changes in emissions brought about by climate change and actions that might be taken to reduce it. Addressing climate change through the reduction of climate-forcing emissions will require major changes in fuel uses and in energy-production and end-use technologies. These changes, in turn, will have significant effects on air quality related emissions. Because a number of air pollutants and pollutant precursors have the power to affect climate change, it is important to take these changes into account and to pursue climate and air quality policies that generate synergistic benefits for both problems.

Should the decision be made to adopt risk-based multipollutant air quality management, we recommend the following high-priority actions for developing the knowledge needed to enable this transition:

Multipollutant Air Quality Management Recommendation 1: *Improve the ability to assess pollutant exposure.* Achieving the objective of risk-based multipollutant air quality management will require improved characterization of human exposure to a wider range of air pollutants within a broader spectrum of microenvironments and exposure scenarios. This requirement is the most important advance needed to improve our understanding of pollutant-health relationships not only for air quality management but also for sharpening our understanding of the effects of air pollution on human health and ecosystems. Achieving this goal will require new or enhanced measurement methods and monitoring strategies (see Multipollutant Air Quality Management Recommendation 4) as well as modeling tools that support improved exposure assessment for both human-health and ecosystem-effects studies and a commitment to verify the exposure estimates provided by these measurement systems and models. These systems, strategies, and models will need to provide information with the temporal and spatial resolution needed to represent the ambient concentration gradients associated with the pollution sources of concern. They will need to account for geographically specific outdoor conditions, infiltration into buildings and vehicles, and human activity patterns. These data must go beyond the information needed to document concentration distributions and trends of regulated pollutants for conventional compliance purposes and include other pollutant species that may pose health or environmental risks.

Multipollutant Air Quality Management Recommendation 2: *Expand the focus of health and ecosystem effects research to include the effects of exposure to multiple pollutants and place increased emphasis on this problem.* Encourage the formation of broad multidisciplinary research teams (including atmospheric, exposure, health and ecological scientists) and direct these teams to focus on the following strategic questions: (1) What are the health and ecological damage burdens of air pollution in relationship to other environmental stressors? (2) Which pollutants and combina-

tions of pollutants actually cause which effects, which pollutants dominate these effects, how do they interact, and how can we reduce uncertainty about the effects of exposure to single pollutants? (3) Is it feasible to group pollutants according to chemical structure or type, or some other feature, in order to expedite research on the effects of exposure to multiple pollutants? (4) Can we construct objective metrics for prioritizing health versus ecosystem effects? The emphasis in addressing these questions should be on improving our understanding of the risks of exposure to pollutant mixtures and of the relative risks of exposure to individual pollutants.

Multipollutant Air Quality Management Recommendation 3: *Improve emission information and emission control technologies.* Improvements in emission information should include (a) implementing the recommendations of the NARSTO Emission Inventory Assessment (NARSTO 2005), (b) improving communication between the health effects and emissions information development communities to ensure that emissions inventories include, to the extent feasible, all substances thought to pose risks to human health and ecosystems, (c) expanding the range of substances and sources that can be measured directly, and (d) encouraging the development of multipollutant emission control technologies that could reduce the cost and improve the effectiveness of emission reduction programs.

Multipollutant Air Quality Management Recommendation 4: *Modify the designs of air quality measurement programs to enhance support for multipollutant air quality management.* Present air monitoring programs in North America are designed primarily to demonstrate compliance with ambient air quality standards. Nevertheless, they do support some multipollutant surveillance. Thus within the current system, there are opportunities to shift resources to improve support for multipollutant air quality management. Examples include: (a) expanding measurement of oxidants, speciated volatile organic compounds, and particulate organic compounds, (b) expanding the measurement capabilities of current monitoring systems by using advanced instrumentation already proven to be reliable, (c) coordinating current measurement objectives with those needed to support epidemiological studies, including provision for at least occasional intermittent sampling in areas of strong concentration gradients (e.g. roadway zones), and (d) conducting special campaigns to measure exposure-related parameters and non-regulated species including oxidants, a wider range of reactive nitrogen species, and ammonia. In Canada, there is a need to add one or two multipollutant sites in the northern portion of the country in order to improve coverage in remote regions. In Mexico, there is a need to continue expand permanent measurements in cities and population centers other than the Valley of Mexico, and add at least one regionally representative multipollutant site in rural, central, or northern Mexico.

Multipollutant Air Quality Management Recommendation 5: *Undertake one or more pilot studies of the feasibility of implementing a risk-based, results-oriented multipollutant approach to air quality management.* The current technical capabilities for developing coordinated emission reduction approaches to controlling air pollution and implementing multipollutant air quality management at *Levels 1* and

2 should be expanded. As a first step in a transition to a multipollutant approach, additional pilot studies, such as the one recently completed in Detroit, Michigan are needed to assess the feasibility and advantages of coordinating management of criteria pollutants and air toxics. They are also needed to examine the extent to which we can demonstrate accountability and use it as a management tool. Although some initial steps have been taken in the United States to explore multipollutant air quality management approaches (principally at *Level 2*), these efforts have not encompassed the scope proposed here, which implies development of approaches to implementing *Level 3* and ultimately *Level 4* multipollutant air quality management plans.

Multipollutant Air Quality Management Recommendation 6: *Analyze the potential effects of technological change, especially those changes related to climate change, on future air quality and its effects on human health and ecosystems.* The objective of this research should be to characterize the effect of new fuels or changes in primary production or end-use energy technologies, adopted to reduce greenhouse gas emissions and climate-affecting particles, on air quality as well as the effect of future air quality management actions on the production of climate-forcing agents. The scope of this research should also include investigations of how a changing climate might affect natural emissions of greenhouse gases, particles, and greenhouse gas and particulate precursors.

1.4.2 Accountability

Accountability is a formal procedure for determining whether a given air quality management action or combination of actions have achieved their intended benefits. In addition to measuring the effectiveness of air quality management actions, accountability can also be part of a process of continuous improvement. Each step down the accountability chain provides information that can be used to improve the effectiveness or, perhaps, lower the cost of achieving air quality management goals; however, with each step it becomes increasingly difficult to establish definitive outcomes and a clear cause and effect relationship.

Considerable evidence shows that past air quality management actions have resulted in improved air quality (i.e., reduced ambient concentrations) for criteria pollutants. Emerging evidence also shows that actions taken to reduce ambient concentrations of ozone and particulate matter have led to reductions in adverse health effects associated with exposure to ambient concentrations of these pollutants. Reductions in emissions of acid-forming substances, especially sulfur dioxide, have led to reductions in acidic deposition and improvements in water quality in many sensitive surface waters. *However, no formal, complete retrospective analysis, through the accountability chain, has been performed on a specific air quality management action to determine whether the expected results of the action was achieved in practice. Consequently, we strongly recommend a formal, quantitative demonstration that mandated emission reductions have been achieved along with the expected changes in ambient concentrations or deposition.*

Accountability Recommendation 1: *Two or more retroactive test cases should be undertaken to demonstrate the current capability for determining full accountability for past major air quality programs or rules.* These test cases should bring together the best available information in a formal assessment down the accountability chain and serve as a starting place for future accountability improvement.

As the first step in implementing this recommendation, we strongly recommend that the ability to achieve at least step 2 of the accountability chain (verification that actual or estimated emission changes resulted in the expected changes in ambient concentrations or deposition) be explored before accountability is mandated as a component of future air quality management decisions. *The difficulty in determining whether discrepancies between predicted and observed changes in ambient air quality or deposition are due to errors in emission information, deficiencies in our understanding of the relevant atmospheric chemistry or atmospheric processes, errors or deficiencies in the representation of important chemical or other atmospheric processes in the air quality models used, the impact of predicted versus actual meteorology, or in the way the models were implemented (or all of the above) should not be underestimated.*

In Mexico, the principal source of data to establish trends in ambient air quality for criteria pollutants is the Valley of Mexico (Mexico City). To facilitate the establishment of broader accountability in Mexico, we recommend that development of their national monitoring network be pursued as rapidly as practical. Further, there is a need in Mexico for a sustained survey of air toxics in urban areas beyond currently conducted in Mexico City.

Achieving step 4 of the accountability chain (verification that reductions in exposure have led to improved public health or reduced damage to sensitive ecosystems) will not be easy. *Epidemiological and toxicological research indicates that common air pollutants have adverse health effects, but determining the health benefits of gradual reductions in the ambient concentrations of these pollutants due to a specific air quality management action is difficult. Few, if any, health impacts associated statistically with air pollution are caused solely by exposure to air pollution, and the portions attributable to pollution are uncertain. Moreover, demography and other factors that affect exposures leading to health effects can change on the same time scale as improvements in air quality.* The strongest evidence for human health benefits from reductions in air pollution comes from so-called “natural experiments” or “intervention studies” in which large and relatively rapid reductions in emissions leading to improvements in air quality are accompanied by reductions in certain health burdens among the affected population. In contrast to intervention studies, most air pollution control measures take effect gradually, and most estimates of pollution-response relationships take the form of concentration-effect slopes or potency factors (i.e., risk per unit of pollutant concentration). Health gains can result from reduction of exposure, reduction of potency (in the case of multi-component classes such as PM), or both. Misattribution or underestimation of health gains can occur if factors unrelated to pollution, but capable of mitigating or masking the change in health burden, change over the same period that pollutants are reduced in concentration or potency. Thus, demonstrating that specific air

quality management actions have resulted in improvements in human health (or ecosystem function) is extremely difficult, and it can take a long time (perhaps 20 years or more) for the signal (e.g., reduced mortality due to air pollution exposure) to emerge from the noise (all other confounding factors). Such demonstrations can probably be done and, as stated above, there is emerging evidence of the population health benefits of reduced exposure to ambient concentrations of lead or fine particles. Demonstrating changes in health effects related to pollution exposure requires carefully designed epidemiological experiments that are executed in concert with the air quality management action and maintained over extended periods of time. It may also be difficult to sort out which air pollutant may be responsible for what effect. People and ecosystems are exposed simultaneously to many air pollutants and exposure to them may be highly correlated. It is difficult to determine the effects of individual pollutants because little is known about the combined effects of exposure to multiple pollutants, which may not be additive. It is also possible that the air pollutant thought responsible for a given effect may only be an indicator of exposure to some other substance that is correlated with it.

Accountability for effects of air pollution exposure from deposition to vulnerable ecosystems has advanced in similar ways to that of human health effects, especially for acidification of aquatic systems. Changes in terrestrial ecosystems with pollution reductions have been difficult to verify not only for acidic deposition, but also for oxidants, trace metals, and persistent organic pollutants. Changes in chemistry of vulnerable surface waters from reduction in sulfur oxide emissions and sulfate deposition have been documented semi-quantitatively in accordance with expectations of emission reductions in eastern North America. However, the recovery of biota has been far slower than the response in water chemistry. Research to date has shown the difficulty in attributing changes in managed or unmanaged terrestrial ecosystems systems to reductions in exposure to contemporary levels of air pollution (including acids, acid gases, oxidants, metals or persistent organic pollutants) for reasons similar to those found for humans. Additional support for long-term surveillance of representative ecological sites would assist the verification of expected changes in relation to pollution exposure, not only in water and soils chemistry, but also in biological changes involving species survival and diversity.

Accountability Recommendation 2: *Verify and improve emission estimates from model-estimated source categories.* Characterizing and verifying changes in emissions from sources equipped with continuous emissions measurement systems are relatively simple. However, it is much more difficult for the large number of mobile, complex industrial, small point-sources, and area-sources for which emissions must be estimated by means of emission models. *Uncertainties in, and in some cases the lack of information on, emissions responsible for adverse health and ecosystem outcomes remains a fundamental barrier to implementation of formal accountability procedures.*

Model verification and improvements must include better speciation information that encompasses, to the extent possible, all substances known or suspected to adversely affect human health or ecosystems. Specific examples include:

- Improving on-road and non-road mobile source emission models by measuring exhaust and evaporative emissions from statistically representative samples of in-use vehicles or equipment for a representative range of environmental conditions and operating modes. Improved characterization of volatile organic compounds, semivolatile organic compounds, and carbon particulate emissions are of particular interest. The use of micro-sensors for continuously measuring oxides of nitrogen, carbon monoxide, volatile organic compound emissions coordinated with measurements of carbon dioxide or fuel consumption would be a valuable innovation.
- Improving estimates of ammonia emissions from agricultural sources and verifying these models for the range of climatic conditions, agricultural economies, and agricultural practices across North America.
- Instituting focused research and development programs for characterizing emissions and improving emission estimates for important source categories (including climate-relevant emissions such as those from transportation and industrial sources as well as emissions of air toxics and nitrogen species), which will vary by country and by region.
- Increasing information exchange between the health effects and emissions characterization communities to ensure that emissions thought to pose the greatest health-risk potential are measured or modeled accurately over a range of space and time scales. Such emissions information may include substances not included in traditional emissions inventories.
- Maintaining continuity and comparability in a time-continuous record of emissions inventories to enable retrospective analyses of past air quality management actions. Particular emphasis needs to be placed on documenting changes in emissions developed from models that are frequently updated to incorporate methodology improvements. Not having this information hampers the ability to compare results over time.

An important priority for Mexico should be to undertake an assessment of the adequacy of current emission inventories for supporting an accountability assessment of the effectiveness of current air quality management actions in reducing concentrations of ambient pollutants. This demonstration could focus initially on the effects of reducing sulfur concentrations in transportation-sector fuels.

Consideration should also be given to increasing, where practical, the number of large point sources in North America equipped with continuous emission monitoring systems. Furthermore, we recommend that a significant level of funding be provided, through mechanisms such as the U.S. Small Business Innovation Research program, for the development of small, potentially low-cost, emission measurement systems that would increase the number of source categories that could be measured directly either on an operational basis or for improving the accuracy of emission models.

Accountability Recommendation 3: *Identify reliable biomarkers of exposure for a larger number of air pollutants.* Air quality goals for criteria air pollutants are generally expressed in terms of ambient concentrations, and it is assumed that attainment of these goals will be reasonably protective of human health. However, knowing broad-scale average ambient concentrations is often insufficient for deter-

mining human exposure and, eventually, dose. First, for many pollutants current ambient monitoring and air quality modeling do not supply information on the spatial and temporal scales relevant to actual individual exposures. Ambient concentrations of pollutants associated with many sources of concern, such as high traffic-density roadways or toxic air pollutant “hot spots,” may vary sharply with distance from the source, with season, or with time of day. Second, estimating exposure to pollutants of ambient origin requires knowledge of how and for how long affected individuals move through this concentration space, what they are doing while they are there, the infiltration of ambient pollutants into indoor environments occupied by affected individuals, as well as other factors.

Given the difficulty of estimating exposure from measurements and modeling, identification and validation of additional biomarkers of exposure to a wider range of air pollutants could greatly facilitate accountability analyses and should be a priority research objective. Except for lead and carbon monoxide, exposure to criteria air pollutants is generally not associated with specific, identifiable effects or biomarkers. The situation with respect to hazardous air pollutants, however, appears to be more hopeful. There has been considerable progress in identifying biomarkers of exposure to hazardous air pollutants, particularly for carcinogens. These markers are useful for characterizing total exposure to many compounds that are found in the air, noting that most of these species can also enter the body via other routes. Despite these challenges, the availability and utility of biomarkers of exposure to air pollutants is improving, and their use as indicators of exposure are expected to receive increased attention in multipollutant studies.

Accountability Recommendation 4: *Rethink current monitoring network design and sampling strategies and focus their mission on providing the information needed for improved exposure assessment. Continue the development of improved exposure assessment models and methodologies for exploiting exposure-focused observations.* For pollutants having no practical biomarkers, exposure must be estimated using a combination of measurements and modeling tools. Measurements and modeling tools may also be needed to supplement the information deduced from biomarkers. If the ambient concentrations of the pollutant or pollutants in question are relatively homogeneous in space and time, assessing the impact of air quality actions on exposure is relatively straightforward. Estimating exposure for pollutants presenting significant spatial and temporal variability, however, will require improvements in exposure modeling procedures and monitoring network design. Given sufficient investments, we believe that significant improvements in exposure information are possible within the near future (i.e., five to ten years).

The spatial and temporal detail required for exposure assessment cannot be generated by monitoring alone. Exposure characterization will require a more nuanced approach that combines long-term monitoring measurements with modeling and intensive diagnostic measurement campaigns that provide practical estimates of the appropriate ambient concentrations. These estimates, combined with improved exposure models, can then be used to provide estimates of individual exposures (as needed for some air toxics), or population exposures (as needed for some criteria air pollutants). Development of approaches for providing the kinds of detailed ambient concentra-

tion fields needed for exposure assessment will require implementation of a number of field studies in several venues across North America in order to test and evaluate the new methods, monitoring network designs, sampling strategies, and data analysis procedures that would be required to take accountability to this level of detail.

Accountability Recommendation 5: *If accountability is adopted as a tool for evaluating and adjusting air quality management actions, it must become an integral part of the air quality planning and rulemaking process.* A technically credible accountability program would demonstrate the linkages in the accountability chain from emissions to exposure; it would demonstrate that the accountability metrics can be determined to some reasonable level of statistical uncertainty; and it would need to be adequately funded.

1.5 Final Remarks

A multipollutant approach to air quality management is currently feasible through *Level 2* (attainment of standards for individual pollutants, but with increasing attention to co-benefits attainable through coordinated emission reductions); coordination of air quality management actions at this level could have considerable benefit. Given sufficiently accurate emission information, accountability through Step 2 (verification that the air quality management action in question has achieved the expected reductions in ambient concentrations or deposition) is feasible and could provide valuable information for assessing or improving air quality management actions. However, it is recommended that this conclusion be tested before this level of accountability is made a formal part of the air quality management system.

Implementing higher levels of multipollutant air quality management and accountability is problematic in the near term, because key exposure and human or ecological health information is not available. The exception might be in considering a multipollutant approach that focuses on exposure. Given improved exposure characterization, air quality management actions could be prioritized according to which might be most effective in reducing exposure for broad population categories to the pollutants or combinations of pollutants presenting the greatest risks as we currently understand them.

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