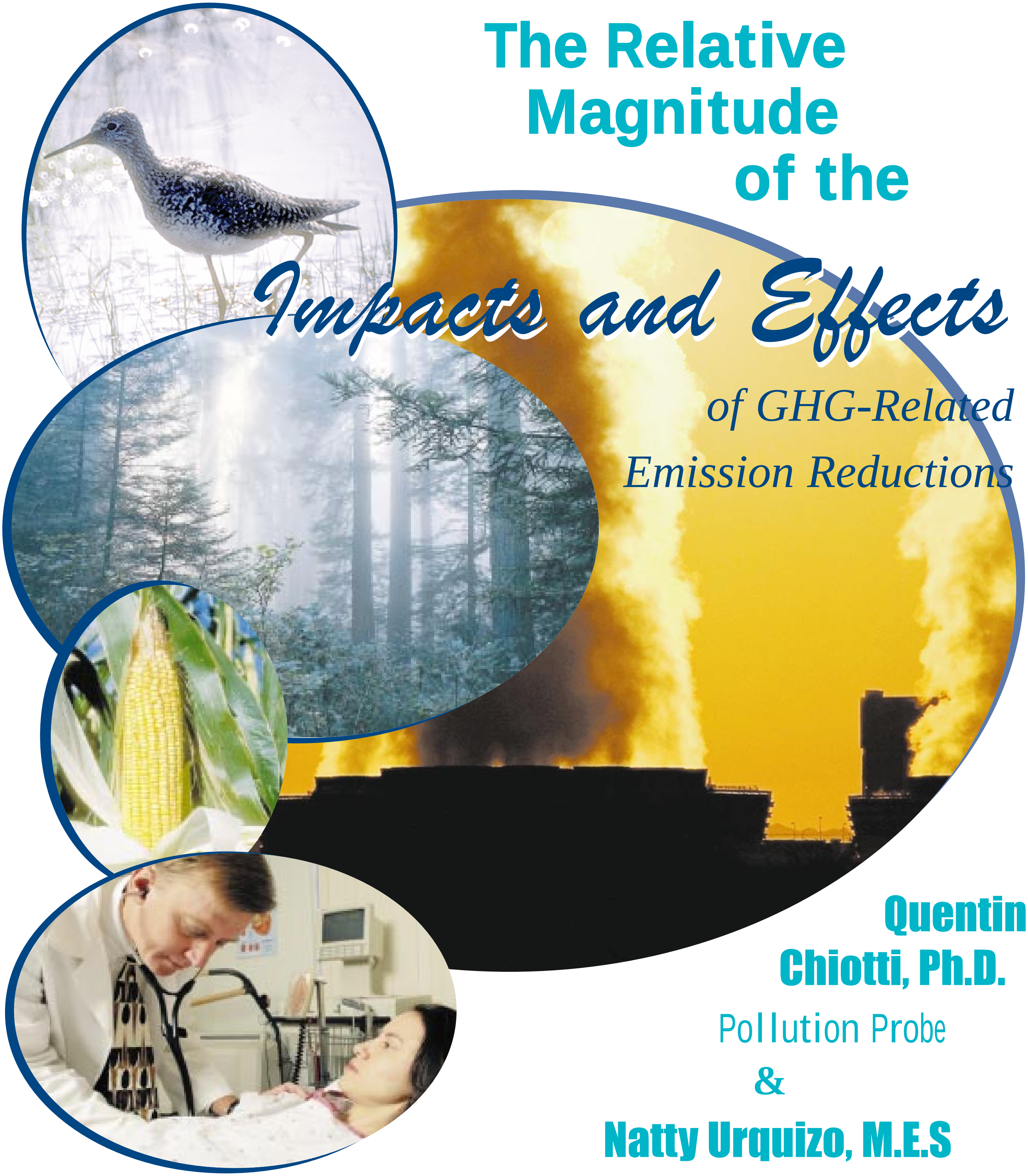
The Relative Magnitude of the *Impacts and Effects* of GHG-Related Emission Reductions



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EXECUTIVE SUMMARY

The development of an effective national implementation strategy for climate change represents a significant policy challenge to the signatories of the Kyoto Protocol, including Canada. In selecting from the response strategies available to Canada, policy- and decision-makers are advised to consider the full welfare implications of abatement measures. A complete assessment of net benefits should also consider the co-benefits that result from direct actions to reduce the accumulation of GHGs in the atmosphere.

This scoping paper provides a preliminary assessment of our current state-of-knowledge regarding the co-benefits associated with climate change mitigation. The assessment focuses upon the relative magnitude of the impacts and effects from GHG-related emission reductions. One of the benefits associated with mitigation is that a decrease in GHG emissions will also result in reductions of other air pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO), volatile organic compounds (VOCs), particulate matter (PM), ground-level ozone (O_3), heavy metals and other toxic pollutants. These pollutants are linked to other air issues such as stratospheric ozone depletion, air quality and acid deposition, which are known to have a wide range of adverse impacts and effects upon ecosystems, environment, social welfare and human health. Benefits through reduced impacts and effects may also result from the actions themselves to reduce GHG-related emissions. Given the enormity of the problem and the extensive literature on the subject, this paper is intended to provide an initial outline of the complex processes, interactions and uncertainties which characterize the issue.

Preliminary estimates suggest that the costs of impacts and effects in Canada from climate change could be between $3.5 and $24.5 billion per year, if effective actions at mitigation and adaptation are not undertaken. On a global basis, it is estimated that a 50% reduction in GHG emissions are needed to stabilize current atmospheric concentrations. Thus, responding to climate change will require greater consideration of adaptation, in addition to mitigation actions which benefit populations locally.

The Kyoto protocol represents a significant opportunity to address the whole atmosphere from an integrative science and policy perspective through GHG-related emission reductions. The greatest net effects will depend on many factors, including the interactions among pollutants and air issues, and the specific measures to reduce GHG-related emissions. The processes shaping the impacts and effects on ecosystems, the environment, social welfare and human health are also dynamic. Some relationships may be synergistic, counteractive or non-linear.

Understandably, the size of the co-benefits resulting from GHG-related emission reduction depends upon the nature of the actions taken, the magnitude and duration of exposure to specific pollutants, and the sensitivity of the exposed population, among other factors. Benefits from actions to reduce GHG-related emissions accrue in the near term and largely in regions where the mitigation actions are expected as well.

Reductions in specific pollutants are determined by several factors such as the source of emissions, i.e. stationary or mobile, as well as energy type, i.e. coal or natural gas. Some U.S. studies have estimated reductions in SO_x and NO_x to range between 3-32% with smaller reductions likely to occur for total suspended particles (TSP) and VOCs. Model simulations from the

1995 Climate Action Network Greenhouse Gas Management Plan estimate that a 6.5% reduction of CO_2 below 1990 levels in Canada would result in emission reductions of 24% for SO_2, 16% for NO_x and 13% for VOCs.

None of the Canadian studies apply dose-response functions to determine impacts upon ecosystems or effects upon the environment, social welfare or human health. Consequently, the co-benefits that may result from GHG-related emission reductions have not been valued for Canada. In response to these knowledge gaps an assessment framework is presented, which:

- Extends the range of pollutants to include pollutants that relate to all air issues.
- Considers interactions between air pollutants and air issues, including potential additive, synergistic or counteractive relationships.
- Examines emission reductions, impacts and effects in relation to present air issue targets.
- Evaluates impacts on the atmosphere and ecosystems (terrestrial and aquatic).
- Determines the effects on the environment (agriculture and forestry), social welfare and human health.
- Addresses impacts and effects from the actions themselves.

The primary source of GHG emissions in Canada are fossil fuels, which also account for about 55% of SO_2, 90% of NO_X, 55% of VOCs and 90% of CO. Presently, there are some key policies to control air pollutants, such as the Canada-U.S. Air Quality Agreement which deals with acid deposition, ground-level ozone and particulate matter. The addition of a GHG emission reduction plan will contribute substantially to the reduction of many of the individual pollutants for which there are already emission reduction goals. Actions to reduce GHG emissions could help meet or exceed emission reduction targets for other air pollutants. For example, GHG reductions could help reduce SO_2 emissions beyond the 50% target set for 2010. When addressed from an integrative perspective, a well thought-out GHG reduction plan will also generate added benefits for aquatic and terrestrial ecosystems. The most obvious gains will be made in reducing the precursors to acid deposition, ambient particulate matter and ground-level ozone. Other benefits may occur due to the GHG-based reduction of pollutants in the air issues. More specifically, some examples of impacts and benefits include:

Atmosphere:

- Greenhouse gases that contribute to stratospheric ozone depletion are suspected to transform mercury from a gaseous to particulate state.
- Reductions in GHGs could impact the Long Range Transport of air toxic substances, such that the rate of the “grasshopper effect” would be slowed down from what could occur with a global increase in temperature.
- Reductions in GHG will help reverse the downward trend of oxygen concentrations in the Northern Hemisphere.
- Sulphate aerosols offset global warming by absorbing and scattering solar radiation, and mask temperature increases by more than 25% on a regional scale.
- Greenhouse gas-related emission reductions will result in less CO being released into the atmosphere, therefore more OH will be available for reaction with gases such as methane (CH_4) and halogenated CFCs, thus reducing their lifespan.

Ecosystems:

- Reduced ground-level ozone concentrations would especially benefit plants since they are more sensitive than humans to ozone stress.
- It is estimated that 20-30 million hectares of Canada's forests are exposed to sulphate and nitrate deposition in amounts near critical loads.
- Due to acid deposition, large quantities of calcium and magnesium are exported with drainage to a point where the maintenance of soil fertility and forest productivity is endangered. Soil fertility is rapidly being degraded at the present rate of acid deposition.
- Acid deposition is closely linked to the accumulation of mercury in fish. Further reductions of acid deposition as a result of GHG-related emission reductions will benefit the health of the upper levels of the food chain.
- Greenhouse gas-related emission reductions in SO_2 beyond the current 50% policy goal could make it possible for approximately 890,000 hectares of lakes in the southeastern Boreal region meet the critical load criterion (pH 6.0). It would also help prevent 162,000 fish populations from perishing.
- Greenhouse gas-related emission reductions would result in less acid deposition and more dissolved organic carbon, thus permitting less UV-B penetration into aquatic ecosystems.
- The positive effects of CO_2 enrichment on vegetation would be enhanced if the adverse effects of acid deposition and ground-level ozone are reduced.

Human health:

In evaluating the effects of reducing GHG-related emissions, the benefits for human health from improved air quality have received the most attention, especially in regards to particulate matter. In most studies the valuation estimates of benefits for human health tend to dominate impacts on ecosystems, and effects on the environment and social welfare, by several orders of magnitude, with the value of avoided premature mortality greatly exceeding those for reduced morbidity. For example, estimated benefits on a per capita basis for Maryland have been valued at US$116.80 for human mortality, US$5.60 for human morbidity, and between US$1.60 – US$2.00 for visibility.

A review of the broader literature, however, suggests that most estimates of co-benefits may be conservative. First, our knowledge of non-health impacts and effects is more extensive than what has been presented in previous assessments. Second, actions to reduce GHG-related emissions themselves (e.g. actions not directly emission related) generate additional external costs and benefits for ecosystems, the environment, social welfare and human health. Third, there is insufficient information on these impacts and effects for estimating the value of benefits. Two key conclusions result: (i) the overall magnitude of benefits are greater than previously estimated; and (ii) the relative magnitude of non-health impacts and effects are greater than previously estimated.

In assessing the relative magnitude of effects upon the environment, social welfare and human health, it is important to note that:

- Acid deposition has a greater effect upon forests than ground-level ozone.
- Ground-level ozone has a greater effect upon agriculture than acid deposition.
- In comparative terms more is known about the effects of acid deposition on forests than other atmospheric stresses such as ground-level ozone and UV-B.

- It is estimated that acid deposition reduces forest productivity by 10%.

- The value of reducing seasonal mean ground-level ozone levels at or below 35 ppb for improved agricultural productivity in Ontario is estimated to be between $17-70 million annually.

- Reductions in GHG-related emissions (especially SO_2, NO_3, O_3 and PM) will benefit social welfare by improving visibility and decreasing material soiling and degradation.

- Recent human health studies of air pollution in Canadian cities have demonstrated that the ambient air pollution mix (which includes all gaseous pollutants) had a greater effect than PM_{10} and even $PM_{2.5}$. Of the criteria pollutants, NO_2 was found to have the largest effect on mortality with a 4.1% increased risk, followed by ground-level ozone (1.8%), SO_2 (1.4%) and CO (0.9%).

- It is estimated that 16,000 premature deaths due to air pollution occur in Canada every year. In southern Ontario, it is estimated that 1,800 premature deaths can be attributed to PM.

- By the end of the second decade of the next century, studies estimate just over 700,000 premature deaths would be avoided globally on an annual basis due to the PM emission reductions associated with reductions in GHG emissons of 15% by the year 2010 for developed countries and 10% for developing countries below 1990 levels.

- The number of avoided premature deaths is estimated to be 138,000 in developed countries, and specifically 33,000 in the U.S. By extension, 3,300 premature deaths in Canada could be avoided.

- For the U.S., this estimate is the same order of magnitude as occurs from human immunodeficiency and chronic liver diseases. However, since these estimates are based solely on PM, they are conservative and underestimate the total number of avoided deaths and reduced morbidity attributed to the full range of criteria pollutants such as NO_2, SO_2, ground-level ozone and CO.

- Statistics for reduced morbidity are difficult to document; hence, these benefits may be underestimated in the literature.

- Depending upon the source, reductions in GHG-related emissions could also reduce emissions of air toxics. Toxic pollutants such as arsenic, cadmium, chromium, lead and mercury are known to cause cancer or in some cases act as nerve toxins. In Ontario, the substitution of natural gas for coal in electricity generation would result in an 83% reduction of SO_2 emissions from this source, in addition to equal reductions in air toxics.

Actions to reduce GHG-related emissions can also generate impacts and effects upon ecosystems, environment, social welfare and human health. For example,

- A modal shift in transportation from single occupied vehicles into public transit will result in human health benefits through reduced traffic fatalities. Additional benefits include reductions in unwanted noise, traffic congestion and consumption of natural resources, as well as helping to preserve prime agricultural land.

- In developed countries, aggregate external costs of land transportation can reach levels up to 5% of GDP, with the following distribution: air pollution (excluding global warming), 0.4%; noise, 0.2%; accidents, 1.5%; and congestion, 2.0%.

- Improved energy efficiency in residential homes and commercial buildings can also generate benefits for indoor air quality. If combined with improved building standards, there will be an additive benefit by increasing the resilience of homes and buildings to the impacts of climate change (e.g. extreme events).

This paper serves as a useful “reference library” from which to assess co-benefits. The Issues Tables engaged in the process to develop a national implementation strategy may find the information and bibliography contained in this document to be helpful when assessing the environmental, social and health impacts of their response options. The paper also provides additional information on co-benefits for the quantitative modelling initiative currently underway for the *Analysis and Modelling Group*. Many knowledge gaps have been cited throughout the paper, and future work should address (i) uncertainties in the interactions between atmospheric issues and their synergistic, antagonistic and cumulative impacts and effects; (ii) the valuation of these benefits, particularly those for ecosystems, the environment and social welfare; and (iii) the indirect benefits from the actions that reduce GHG-related emissions.

In pursuing these knowledge gaps, we need to recognize the importance of scale in shaping co-benefits. Atmospheric issues operate at various spatial and temporal scales, but those pertaining to air quality are largely immediate and regionally specific. This is also true for benefits that will occur from the actions themselves to reduce GHG-related emissions. Further, scenarios of emission reductions in the U.S. have demonstrated that significant human health benefits may accrue in Ontario and eastern Canada. This reflects the importance of bi-national emission reductions in terms of generating GHG reductions and co-benefits.

An integrated-qualitative approach that draws upon expert judgement to assess co-benefits may be the most practical and productive method to overcome these uncertainties and knowledge gaps. For Phase II, an assessment needs to be developed along the following five pathways:

- Focus on estimating impacts and effects on ecosystems, environment, social welfare, human health and the actions themselves to reduce GHG-related emissions, and assigning relative values to these benefits.

- Estimate the full suite of co-benefits from the most likely actions that may be adopted in the national implementation strategy.

- Assess the GHG options proposed by the respective Issues Tables in terms of co-benefits, and prepare a qualitative analysis.

- Simultaneously undertake this assessment at an urban-centred regional scale, where the methodology can be further refined and important lessons learned.

- Situate this regional assessment within a national context and identify other regions in Canada where similar assessments should be implemented.

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1.0 PURPOSE AND OBJECTIVES

Global climate change represents one of the most significant environmental challenges facing humankind. There is broad scientific consensus that greenhouse gases (GHG) (e.g. Carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Ozone (O_3) and Halocarbons (HCFCs, PFCs and SF_6)) generated by anthropogenic activities are reaching levels of atmospheric concentration which are having a "discernible influence on the global climate" (Houghton *et al.*, 1996, p. 4). This concern has led to an international response to the issue, initially with the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, followed by the Kyoto Protocol in 1997.

Responses to climate change include policies directed at "mitigation" and "adaptation". Mitigation refers to measures designed to reduce human-induced emissions and, consequently, atmospheric concentrations of GHG, whereas adaptation refers to measures designed to reduce impacts from and vulnerability to climate change. Undoubtedly, developing an effective suite of mitigative and adaptive responses to climate change represents an enormous challenge to all signatories of the Kyoto Protocol, and Canada is no exception. At their December 11-12, 1997 meeting, for example, Canada's First Ministers discussed the Kyoto Protocol and agreed, among other things, that the development of an effective national implementation strategy required:

> a thorough understanding of the impact, the cost and the benefits of the Protocol's implementation and of the various implementation options open to Canada (Barclay, 1998a).

Generally, mitigation has received much greater attention than adaptation in the science and policy literature (Watson *et al.*, 1996), with emission trading, increasing carbon sequestration via sinks, and the co-benefits associated with reducing GHG-related emissions receiving particular attention in North America. A common approach in analyzing policies for GHG abatement has been to focus upon their costs and potential for reducing the rate of increase in atmospheric concentrations vis-à-vis the cost of impacts from climate change if it continues as projected without effective emission reduction. This is often referred to as comparing the "cost of mitigation" to "the cost of inaction". Such comparison, however, would provide an incomplete picture of the full welfare implications of abatement measures. Many actions that slow atmospheric GHG accumulation will also generate a wide range of co-benefits.

Efforts to halt deforestation, for example, will contribute to the conservation of the world's biological diversity, while CO_2 emission reductions will reduce other environmental problems related to fuel combustion. By achieving reductions in "conventional" atmospheric pollutants, local and regional air quality will be improved, in addition to impacting positively on efforts to reduce associated environmental and human health impacts. Failure to adequately consider ancillary or co-benefits could lead to:

i. an incorrect assessment of the "net costs" of mitigation policies;
ii. an incorrect identification of "no regret" levels of GHG mitigation; and
iii. an unnecessarily expensive policy because of its failure to fully exploit potential co-benefits (Burtraw and Toman, 1997).

Although estimates of co-benefits achieved through GHG reduction vary widely amongst studies, it is generally accepted that they could be substantial, amounting to over 30 percent of the cost per ton of carbon reduced, if not greater (Burtraw and Toman, 1997; Pearce *et al.*, 1996).

The purpose of this overview paper is to provide a preliminary qualitative assessment of the relative magnitude of the environmental, social and health effects from actions and measures to reduce GHG-related emissions. The paper outlines the positive and negative impacts and effects of GHG-related emission reductions, which contribute to stratospheric ozone depletion (and increasing UV-B), acid deposition, smog, particulates and hazardous air pollutants. Impacts upon the atmosphere and ecosystems (both terrestrial and aquatic) are addressed, as well as the effects upon the environment (agriculture and forestry), social welfare and human health. A framework for qualitatively assessing the co-benefits of GHG-related emissions is also presented, including the identification of knowledge gaps, areas of uncertainty, and priorities for future analysis. In the latter context, this includes the development of an action plan for Phase II, to use expert scientific judgement to assess co-benefits at the national and regional scales of analysis.

The discussion also describes the complementarity and linkages of this work to other analytical (e.g. quantitative models) and environmental assessments (e.g. a checklist of options for the Issues Tables) currently underway or proposed as part of the climate change national implementation strategy. Collectively, these activities are designed to address the following key analysis questions:

- How might specific actions to reduce GHG emissions affect other environmental emissions/impacts?

- How would changes in GHG and other emissions at specific sources alter the effects on human health and environmental quality?

- How significant would the quantifiable benefits of reducing these emissions or impacts be, relative to the costs of taking action?

- What other effects may be important to consider at least in qualitative terms, especially those that are not directly attributed to improvements in air quality?

- How might actions to reduce other emissions affect GHG emissions?

- What is the least cost strategy to achieve multiple environmental/air quality objectives (Barclay, 1998a)?

In addition, the work will be situated within the broader literature that addresses the benefits of reducing emissions of air pollutants. This includes determining areas where the “weight of evidence” in the literature supports the quantification of specific impacts and effects (over and above those already intended for quantification). Lastly, the results documented in this overview paper provides information that the Issues Tables can draw upon when assessing the environmental and health impacts of options, in addition for the *Analysis and Modelling Group* (AMG) in determining requirements for further work and input to the roll-up phase.

2.0 SCIENCE AND POLICY CONTEXT

Climate change is a global environmental problem, yet the costs and benefits associated with "actions" and "inaction" are temporally and spatially differentiated, distributed unevenly between countries, within regions, and across generations. This helps explain why developing an effective response strategy to climate change represents such an enormous challenge to policy makers. From the perspective of assessing the co-benefits of reducing GHG-related emissions, a useful starting point is to outline the science and policy context of the impacts from climate change, as well as the benefits associated with mitigative measures.

In the latter context, an assessment must contend not only with the GHGs contributing to climate change, but also with other air pollutants and atmospheric issues. Many uncertainties exist in the understanding of these issues, on an individual air pollutant basis, connections to atmospheric issues, and especially in terms of their interactions. Given that there is an extensive literature on climate change and the complexities of the atmosphere, the purpose here is to outline the major science and policy issues associated with them. The importance of temporal and spatial considerations and their implications for assessing the co-benefits of GHG-related emission reductions are also explored.

2.1 Climate Change Impacts

Various general circulation models (GCMs) of the Earth's climate predict that under a 2 x CO_2 scenario, mean annual global surface temperatures will increase between 1 and 3.5°C by the year 2100, representing an average rate of warming that will be greater than anything seen over the past 10,000 years (Houghton *et al.*, 1996). It is anticipated that northern latitudes will experience the greatest temperature change, with greater average warming occurring over land than over oceans, and in winters relative to summers. Although confidence levels tend to be higher in the hemispheric-to-continental scale projections than those on a regional scale, there is general agreement regarding the direction of change in temperature and precipitation for Canada, as well as the coarse regional pattern across the country (Maxwell *et al.*, 1997).

Climate change is projected to be variable across Canada, with greater warming in interior regions compared to those near the coastlines, and greater winter warming in the Arctic compared to southern regions of the country. Net average warming for central and northern Canada could reach between 4-6°C by 2050 AD, decreasing to 3-4°C along its western and eastern coastlines. Quite possibly, these temperature increases could double by the end of the next century, representing a warming that is nearly three times the global average. Although there is less confidence in hydrological scenarios compared to temperature, it is projected that average precipitation and soil moisture will increase during the winter, with decreased net soil moisture and water resources of more than 20 percent occurring in the Canadian interior during the summer. This would result in the greater frequency and intensity of drought conditions. Flooding may occur in many coastal regions, with extensive permafrost and iceberg thaw occurring in the north.

Considerable uncertainties exist regarding the changes in climate variability and extremes, making estimates of the impact of GHG emissions upon extreme events difficult to project. Nonetheless, it is believed that a small change in the mean climate or climate variability could produce a relatively large change in the frequency of extreme events. In Canada, it is likely that the frequency and intensity of both heat spells and convective storms will increase during the summer, with a corresponding increased potential for drought. During the winter, cold spells will be less severe due to warmer temperatures, but the frequency of intense snowstorms and ice storms may increase. While extreme events are difficult to predict, there is little doubt that the insured costs of extreme events have been increasing dramatically, both on a global (Munich Re., 1997) and national (Brun, 1997) basis.

During the decade from 1984-1994, more than $1 billion was paid by the Canadian insurance industry to compensate for losses caused by climatic natural disasters (e.g. weather-related claims arising from hail, floods, thunderstorms, tornadoes, and windstorms). This amount predates many extreme weather events that Canada has experienced in recent years. Some examples are the extensive flooding in the Saguenay region (July 1996) and southern Manitoba (April-May 1997), along with the record amounts of snowfall in the lower British Columbia mainland (December 22, 1996 - January 3, 1997). Record amounts of freezing rain were observed in parts of eastern Ontario, southern Quebec and southern New Brunswick (January 4-10, 1998) and for snow in Toronto and southern Ontario (January 1999). Not surprisingly, there is growing concern that extreme events could impact Canada's natural and human systems to such an extent that they represent a significantly more dangerous risk than changes in the mean climate conditions which cause them (Maxwell *et al.*, 1997; Dotto, 1999).

These predicted changes in climate are expected to have a wide range of impacts and effects upon natural and human systems across Canada. The extent of these effects in terms of their regional and sectoral significance is well illustrated in a recent Environment Canada led assessment of the impacts from, and adaptation to, climate change and variability (Maxwell *et al.* 1997). The first phase of the Canada Country Study covers six regions across the country, twelve sectors and eight cross-cutting issues. Although the study represents a monumental effort to assess the current state-of-knowledge, many gaps remain which limit our understanding of the range and extent of climate change impacts on sectors and regions across Canada.

Depending upon the capacity to adapt, impacts are likely to be greatest in areas such as the natural environment, water resources and human health. There will be a mixture of adverse impacts and opportunities in sectors dependent upon natural resources and sensitive to climate – such as agriculture, fisheries, and forestry. The least impact will be in the more industrialized and less climate-related sectors of the economy, such as transportation, the energy sector, and building and construction. However, in the latter sectors and in some areas where opportunities exist (e.g. northern expansion of agriculture, reduced energy demand during warmer winters, etc.), there is still a risk of severe impacts occurring because of extreme events. Furthermore, it is possible that indirect losses imposed on Canada as a result of impacts occurring in other countries could be as great as, if not greater than, direct impacts. Just as there may be potential benefits to Canada from adverse impacts elsewhere (e.g. new and expanded markets for Canada's energy, forestry, or agricultural exports).

Based on current knowledge, however, there does not appear to be one set of impacts of outstanding importance, sectorally or regionally. Since wealth and degrees of vulnerability are unevenly distributed between and within regions and sectors, the poorer and more sensitive areas are likely to be most severely affected due to lower adaptive capacity. On a regional basis, areas likely to suffer most are (not in any order):

- coastal regions of the Maritime Provinces, especially low-lying areas subject to sea level rise. In this region, the compensatory benefits of warming also seem less likely to occur (the past few decades have witnessed cooling), and rapid changes in fish stocks may also be climate related.

- poorer parts of the Prairie Provinces, especially areas heavily reliant on agriculture, mostly in Saskatchewan. There may be some compensation through longer growing seasons and milder winters, as well as new export markets, but the threat of more severe drought and new pests and plant diseases now seems likely to outweigh such possible benefits.

- Arctic regions, especially Aboriginal populations and communities in the North, where the impacts of climate change will probably be greatest, and where some relatively poorer communities live a traditional way of life dependent on native fish and game. This applies much less or perhaps not at all to the modern communities in the North.

- urban areas, where the impacts of climate change and other atmospheric issues upon human health are expected to be significant (Chiotti, 1999a).

While the literature on impacts and adaptation is extensive, there is a lacuna of research on the costs of climate change impacts, especially for Canada. Typically, there are three different categories of costs associated with climate change impacts:

i. the costs of doing nothing (sometimes known as the costs of inaction);
ii. the costs of autonomous or policy driven adaptive actions to changes in climate that are not avoided by mitigation; and
iii. the costs of residual impacts that will occur despite adaptation.

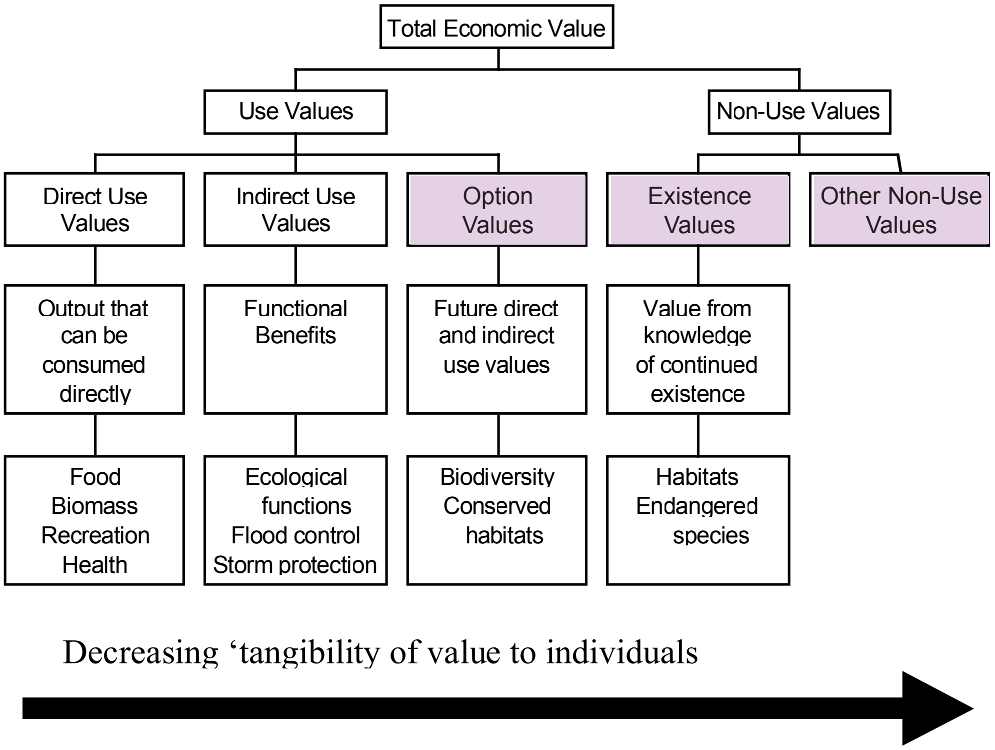
Studies that attempt to compile aggregate cost estimates of climate change impacts (Ayres and Jorg, 1991; Fankhauser, 1994; Nordhaus, 1994) project costs in developed countries amounting to between 1 and 1.5 percent of present-day Gross Domestic Product (GDP). Whereas in less developed countries the projected costs represent a significantly higher percentage of GDP. For Canada, Tol (1995) estimates a 1.5 percent reduction in GDP (using a 1988 base year), which represents a cost of between $8 to $12 billion to the Canadian economy.

These estimates must be viewed with extreme caution, however, due to the many limitations in the methodological assumptions and techniques used in the calculations (Pearce *et al.*, 1996). Such estimates, for example, do not reflect costs arising from non-linearities, where the risk of climate change will lead not to gradual and predictable outcomes, but to relatively abrupt, unforeseen, and potentially catastrophic consequences (Administration Economic Analysis, 1998). The incalculable risk of costly catastrophe scenarios, the possibility of unanticipated impacts, the costs of adaptation to climate change, and the social value of most nonmarket goods and services are merely a small sample of the costs ignored or undervalued in estimates for Canada (Maxwell *et al.*, 1997).

In terms of nonmarket goods and services, there is increasing uncertainty associated with the valuation of non-use environmental assets (Fig. 2.1). This is particularly the case for the value of natural ecosystems which Costanza *et al*. (1997) estimates on a global basis to be worth in excess of US$33 trillion per year, or twice the global Gross National Product. Not surprisingly, existing estimates for Canada are likely to be substantially higher if non-economic costs such as family, community, religion and ecosystems could be valued (Rothman *et al*., 1998). Even a simple reassessment of costs for the U.S., that takes into account variations within and between low and high estimates for each sector considered, produces a range that is greater or lower by an order of magnitude (Demeritt and Rothman, 1998). By extension, the annual costs of climate change impacts in Canada could reach an amount somewhere between $3.5 to $24.5 billion.

Somewhat more confidence exists in estimates of adaptation, at least those in response to current climate. Drawing upon a combination of published material and expert opinion for the early part of this decade, Herbert and Burton (1995) estimate the cost of adaptation to current climate to be over $11.6 billion. As we enter the next millennium, the costs of adaptation to current climate are likely to be considerably higher, and may continue to increase along with climate change. Effective measures to reduce vulnerability through adaptation (and hence reduce adverse impacts) may also lead to the added benefit of being positioned to capitalize upon new opportunities, which may emerge under climate change. However, some impacts from climate change will be inevitable, despite the adaptive measures that are implemented.

Figure 2.1: Categories of Economic Values Attributed Environmental Assets



Source: Rothman et al., 1998

2.2 Responding to Climate Change

The United Nations Framework Convention on Climate Change (UNFCCC) identifies two kinds of response to the threat of climate change: (i) mitigation, and (ii) adaptation. It has been estimated that global emissions of GHGs will need to be reduced by more than 50% over the next century, if atmospheric concentrations are to be stabilized (CGCP, 1997). This implies that while the Kyoto Protocol is an important first step towards achieving noticeable reductions, further reductions will be necessary in the future, requiring the participation of an even greater number of countries, if stabilization will ever be achieved. Under the Kyoto Protocol, Canada has set a target of reducing emissions 6% below 1990 levels by the years 2008-2012, and may have to consider even lower targets in the future. As a country that contributes approximately 2.1% of the global emissions of GHGs, Canada is unlikely to reduce climate change to any significant degree by unilateral action. This might imply that action internationally is needed by Canada to convince other countries to act accordingly, or that adaptation should take an increased role in the national response strategy (where benefits can be captured locally). It is also important to recognize that mitigation actions can themselves produce a wide range of benefits that accrue more positively in terms of time and space.

The benefits associated with mitigation can be assessed in two ways. First, reductions in emissions from baseline projections will generate reduced damages that would otherwise have occurred in the absence of action. These avoided damages, which are often referred to as "abatement benefits", accrue at the global level and are expected to increase over time, generating greater benefits in the future than at present (Pearce *et al.*, 1996). Second, there are the benefits of GHG abatement that spill over into other sectors, specifically through the enhancement of sinks to sequester carbon, and via actions which reduce GHG emissions. The latter, which recognizes that actions to reduce GHG emissions can also reduce other "conventional" environmental pollutants, is receiving increasing attention since the Kyoto meeting.

While it may be possible to achieve significant reductions of non-energy GHG emissions through technological advancements (CHEMinfo Services Inc. and Margaree Consultants Inc., 1998), given existing technology, the most cost-effective method of reducing energy generated GHG emissions is through actions to reduce fossil fuel combustion. This includes energy conservation, energy efficiency, agricultural practices and fuel switching. Reductions in emissions from fossil fuel combustion will also function to reduce a wide range of pollutants. Among them are sulphur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO), particulate matter (PM), ground-level ozone (O_3), volatile organic compounds (VOCs), heavy metals (e.g. lead, mercury) and other toxic pollutants (e.g. acetaldehyde, formaldehyde, organic aromatics, polycyclic aromatic hydrocarbons (PAH), and chlorinated dioxins and furans) (Pearce *et al.*, 1996; CGCP, 1997; Administration Economic Analysis, 1998).

These pollutants are also precursors for other atmospheric issues, such as stratospheric ozone depletion (and increasing UV-B radiation), acid deposition, smog, and hazardous air pollutants. All of which are known to have a wide range of adverse impacts upon aquatic and terrestrial ecosystems, as well as effects upon environmental, social and human health. SO_2 and NO_X are precursors for acid deposition, which have adverse effects upon aquatic and terrestrial ecosystems. SO_2 and O_3 can cause foliar damage in crops and trees, with the latter known to reduce agricultural yields. Particulate matter and secondary pollutants such as sulphates and nitrates are particularly hazardous to human health, impairing both respiratory and cardiovascular systems. Pollutants are also known to impair visibility and damage materials, accelerating the decay of infrastructure (roads and bridges), buildings, statues and monuments. The size of these effects (and therefore the size of the benefits) depends upon the magnitude and duration of exposure to specific pollutants, and the sensitivity of the exposed population, among other factors. Benefits from actions to reduce GHG-related emissions will therefore accrue in the near term, and accrue largely in regions where the mitigation actions occur.

In addition to improving regional air quality and reducing the adverse impacts and effects from other atmospheric issues, the actions themselves could also generate additional "external" benefits. Modal shifts in transportation that involve the movement of drivers from single occupant vehicles into public transit or carpooling, for example, could result in fewer traffic accidents or congestion, while lower gasoline consumption could reduce the risk of tanker accidents and oil spills (Pearce *et al.*, 1996). Abatement avoidance costs are another possible benefit. There are many policies already in place that address specific pollutants and atmospheric issues, which require technological solutions (and capital investments) to reduce emissions. If emission reductions of other atmospheric pollutants are achieved through GHG emission reductions, then emission controls would be unnecessary, and potentially substantial costs for controlling pollution would be avoided. Such costs are estimated to be $1 billion per year in the U.S. (Administration Economic Analysis, 1998).

2.3 The Integration of Atmospheric Issues

On a global basis, and for many countries, policy responses to atmospheric issues have traditionally adopted a “stove-pipe” philosophy, addressing stresses on an individual by individual basis. Canada is no exception in this regard, with a suite of separate policies operating at various scales of analysis (global, bi-national, national, and regional) to address stratospheric ozone depletion (the Montreal Protocol), acid rain and ground-level ozone (Canada-U.S. air quality accord). Assessments of the effects associated with atmospheric issues also tend to adopt a singular focus, such as assessments for acid rain (Environment Canada, 1997a) and ground-level ozone (Dann and Summers, 1997), although in some cases a multiple-issue approach has been taken (OCAC, 1997; TAETG, 1997).

In recent years there has been growing recognition that both science and policy questions pertaining to atmospheric issues need to be addressed from an integrative approach (Munn, 1995). The case for integration has been made at the conceptual level (Munn and Maarouf, 1997; Maarouf and Smith, 1997; Munn, 1997), citing climate change as a key stressor upon other air issues. An assessment of atmospheric issues and biodiversity (Munn, 1996) represents an initial attempt at integration from an applied perspective, but more work needs to be undertaken before this approach can be considered the norm, rather than the exception. An Environment Canada led initiative assessing atmospheric change in the Toronto-Niagara Region (Ogilvie *et al.*, 1997; Chiotti, 1999b; Mills and Craig, 1999) is a further step forward towards integration, addressing multiple air issues from both an emission and impacts perspective (as well as both mitigative and adaptive responses).

By definition, an assessment of impacts and effects from the co-benefits of reducing GHG-related emissions requires the adoption of an integrative approach that takes into account the interactions between atmospheric issues, and the interactions which occur in impacts and effects. A few select studies exist in the literature (Alfsen *et al.*, 1992; Barker, 1993; Complainville and Martins, 1994; Scheraga and Leary, 1994; Burtraw and Toman, 1997). In a Canadian context, analyses of co-benefits are rare, if not only exploratory at best (Haites, 1996). More common are studies which address the co-benefits associated with non-GHG emission reductions – that is, the co-benefits that occur with reductions in SO_2 or NO_X – or those that are focused on specific sources of air pollutants or actions that will reduce emissions (e.g. transportation). A huge knowledge gap may exist in the literature with respect to co-benefits, but the literature upon which an assessment can be extrapolated from is substantial.

The task of assessing the impacts and effects of co-benefits is imposing, but nonetheless necessary from a science and policy perspective given the integrative nature of the problem. MacIver and Urquizo (1999) clearly illustrate the dynamic nature of atmospheric change in Canada, the interactions between air issues, the complex spatial and temporal dimensions, and the importance of addressing the whole atmosphere from an integrated policy perspective. Similarly, the impacts and effects of non-GHG air pollutants upon ecosystems, environmental, social and human health, are comparatively dynamic. Undoubtedly, some actions to reduce GHG-related emissions will generate synergistic relationships, while others will be counteractive in their effect, if not lead to non-linear outcomes.

The case of sulphur is a good example of complexity, from both a science and policy perspective. Pearce *et al.* (1996) note that sulphur abatement achieved through end-of-pipe scrubbers could lead to lower system efficiency, and consequently higher CO_2 emissions. Hence actions to reduce acid deposition in this manner could actually increase atmospheric concentrations of GHG. Similarly, it is now widely known that the accumulation of sulphur aerosols in the atmosphere is causing a reduction in mean temperature, masking the extent of global warming. Warmer temperatures, on the other hand, will aggravate photochemical air pollution, to which SO_2 is a component. The complexity of these interactions underscores the need for a clear understanding of the science and policy implications associated with multiple air issues, but the possibility of synergistic, counteractive and non-linear outcomes exist throughout the co-benefits process. Burtraw and Toman (1997) cite numerous examples of such outcomes, including:

- a shift from coal to biomass for electricity generation could increase particulate emissions in the absence of adequate control equipment;
- increased energy efficiency in the form of better insulated housing could increase indoor air pollution, including radon exposure; and
- increased switching from coal to natural gas raises the issue of fugitive methane emissions, since methane is a more potent greenhouse gas than CO_2.

While identifying effective GHG abatement responses within the broader context of co-benefit considerations is a challenging task, "inaction" by Canadian policy and decision-makers by doing nothing to reduce emissions of either GHG emissions or other pollutants is not a viable option. Under climate change, some conditions in Canada will be aggravated, thereby warranting reductions in the emissions of other pollutants, even if achieved through measures other than those targeted towards GHG emission reduction. For example, under climate change conditions:

- the intensity, severity and frequency of smog episodes is expected to increase, particularly in major urban centred regions; and
- atmospheric concentrations of GHG will increase, affecting the growth of C4 and especially C3 plants through CO_2 enrichment.

In these two examples, failure to reduce the emissions of other air pollutants could further exacerbate the adverse effects associated with regional air quality and limit the beneficial effects from CO_2 enrichment. In the case of air pollution, climate change could generate between US$3.5 - US$27.2 billion additional costs to human health in the United States (Pearce *et al*., 1996).

The Kyoto Protocol thus represents a significant opportunity to address the whole atmosphere and impacts upon environmental and human health from an integrated science and policy perspective, via GHG-related emission reductions. This opportunity, however, should not be viewed as a substitute for adopting an integrated approach to all pollutants, atmospheric issues, and their impacts. Canada has a strong history in reporting on the state of the environment (Environment Canada, 1996), but other countries have gone even further in integrating atmospheric issues into assessments of the environment (Stanners and Bourdeau, 1995). The "Environmental Balance Sheets" developed by the Netherland's National Institute of Public Health and the Environment may be the ultimate example of integrating science and policy in this manner (RIVM, 1999).

As Pearce *et al.* (1996) notes, the question of secondary benefits from carbon abatement should also be distinguished from the more comprehensive issue of the optimal abatement mix with respect to all pollutants. With the Kyoto Protocol, the argument is driven by the implicit primacy of the greenhouse problem, with co-benefits viewed as welcomed side effects, rather than considered in their own right. This is not necessarily the best way to proceed, and perhaps each pollutant (and air issue) should be assessed (and emissions reduced) in proportion to the environmental damage that it causes.

Thus the key message is no longer whether the current state of science provides a powerful rationale to take prompt, prudent action to mitigate climate change (Administrative Economic Analysis, 1998), but rather what steps will generate the "greatest return on investment". Although the answer to this question for the Canadian situation is the focus of this overview paper, Pearce *et al.* (1996) provides some general direction. Interdependencies matter, as does location, and GHG-emission reduction measures should be concentrated in places where the joint benefits of reducing all emissions is highest.

3.0 BUILDING AN ANALYTIC FRAMEWORK

The purpose of this section is to provide the analytic context for assessing the relative magnitude of the impacts and effects of GHG-related emission reductions. A cursory review of the literature that addresses the co-benefits issue directly is the initial focus of this discussion, identifying the key findings, knowledge gaps and uncertainties, which characterize assessments of this issue. This is followed by an outline of the research response and activities currently being developed for the AMG and the Issues Tables. A brief outline of a quantitative modelling exercise under development is presented, including the role of strategic environmental assessment, guidelines to assess environmental and health effects of climate change measures, and the need for an overview paper to scope out the co-benefits issue from an integrated perspective.

In the last section an analytic framework is presented, which attempts to integrate the complex linkages that exist among air pollutants and atmospheric issues, and their impacts upon ecosystems. The analytic framework further considers the potential effects (co-benefits) from GHG-related emission reductions upon several environmental (agriculture and forestry), social and human health endpoints, including effects that may result from the actions themselves to reduce emissions. In the latter case, this involves assessing benefits and costs that are not directly related to emissions and air quality, such as the indirect benefits from cycling and walking (and increased exercise) upon human health.

In developing the research framework, we have combed the scientific literature to identify both qualitatively and quantitatively, the impacts and effects that may occur as co-benefits from reductions in GHG-related emissions. The framework, and the discussions which follow (sections 4, 5 and 6), serves as a data base of our current state-of-knowledge and as such can be helpful in identifying research and knowledge gaps regarding potentially significant damage pathways that have been underestimated in previous environmental assessments of co-benefits.

3.1 Literature Review

The literature that directly addresses the issue of co-benefits from GHG-related emission reductions consists of a small, but growing, number of studies (Pearce *et al.*, 1996; Burtraw and Toman, 1997). Avoided human health effects are the most dominant areas of concern (Lee Davis *et al.*, 1997), although most studies attempt to address a wider range of co-benefits, albeit with varying degrees of scope and depth. There is a standard approach adopted when addressing co-benefits, with most studies incorporating four fundamental steps in their analyses:

- estimating changes in atmospheric conditions between the no-control and control (emission reduction) scenarios;
- estimating human and other populations exposed to these changes in atmospheric conditions;
- applying a set of concentration-response equations that translate changes in atmospheric conditions in environmental and human health outcomes for the affected population; and
- developing valuation estimates of avoided damages.

Studies of GHG-related emission reductions suggest that co-benefits can be significant, yet estimates vary considerably in the literature, due largely to uncertainties and limitations of the data assessed, and differences in assumptions and methodologies employed. Wide variations exist, even though the methods and techniques adopted in studies of co-benefits have been used extensively elsewhere in the literature, and in most cases have been subjected to intensive peer review scrutiny. In general, variations in estimates can be attributed to differences in:

- the air pollutants covered and the mix of energy sources considered;
- the background baseline information on ambient air quality and trends in pollutant emissions;

- the types of emission reduction measures adopted and the role of technology;

- the extent that atmospheric transport of emissions is considered;

- the coverage of impacts and effects; and

- the valuation methods employed.

Differences in any of the above can generate wide variations in estimates of co-benefits, making country (and in some cases regions) comparisons difficult. In addition, spatial aspects can be extremely important in developing estimates of impacts and effects. Regions and countries that are dependent upon coal-fired electricity, for example, will generate a much larger amount of air pollutants contributing to regional air quality compared to areas where hydroelectricity dominates. Similarly, rural regions with low population densities may experience much smaller levels of co-benefits compared to highly populated urban areas. Further, the valuation of human health effects may also be variable, depending upon the method used to estimate costs. The application of willingness-to-pay (WTP) to estimate costs can generate significantly different outcomes than the use of willingness-to-accept compensation (WTC). The selection of discount rates may also greatly influence the valuation of estimates. These are just some of the methodological choices and challenges which contribute to a wide range of estimates of co-benefits.

While a more thorough explanation of these differences can be found elsewhere in the literature (Pearce *et al*., 1996; CGCP, 1998; Administration Economic Analysis, 1998; Abt, 1998), a review undertaken by Burtraw and Toman (1997) of 9 major U.S. studies is particularly useful since it also illustrates how studies can be very selective in estimating the total value of co-benefits. The U.S. studies examined almost exclusively focus on air quality and a select suite of “criteria” pollutants, primarily SO_2, NO_X, VOCs, CO and Total Suspended Particles (TSP), which are generated from electricity fuel cycles (especially emissions from coal-fired plants). Avoided damages for human health are generally the principle focus of analysis, although in some cases the social value of residential and recreational visibility have also been considered. The rationale for this relatively narrow focus upon criteria pollutants and human health effects is based on the belief that they are “likely to constitute the lion’s share of ancillary benefits in the U.S.” (Burtraw and Toman, 1997 p. 1). Collectively, reductions in criteria pollutants are estimated to account for between 90 - 96% of the avoidable damage through all environmental pathways.

Areas ignored or underestimated include impacts and effects from stratospheric ozone depletion, acid deposition and hazardous air pollutants. Further, emissions from transportation sources, impacts upon ecosystems, human health effects from ozone and secondary particles less than 2.5 microns ($PM_{2.5}$) such as sulphates and nitrates, and effects upon water resources, agriculture, forestry and other environmental features of intrinsic value are frequently ignored. The unquantified ancillary emission benefits could be extensive, as suggested in the U.S. Presidential response paper to the Kyoto Protocol (Table 3.1). Toxic air pollutants are rarely included in assessments of co-benefits, ignoring the fact that GHG mitigation strategies will result in additional reductions in a variety of substances that are capable of producing a wide array of health and environmental effects, such as heavy metals, acetaldyhyde, formaldehyde, organic aromatics, polycyclic aramotic hydrocarbons (PAH), and chlorinated dioxins and furans (Administration Economic Analysis, 1998).

The application of dose-response functions to estimate effects of atmospheric stresses upon managed ecosystems, and especially agriculture, has been challenged in the literature. Austin *et al*. (1998) note that while exposure to ambient ozone may be the most significant air pollutant causing adverse effects upon crops, studies examining these effects fail to adequately take into account behavioral response. The effective role of adaptation in reducing the adverse effects of climate change (if not enabling farmers to capitalize upon opportunities arising from climate change) has been well documented in the literature (Easterling *et al*., 1993; Smit, 1993; Rosenzweig and Parry, 1994), suggesting perhaps that effective adaptive measures to other atmospheric stresses may also be possible.

TABLE 3.1 Unquantified Ancillary Emissions Benefits

Effect Category	Effects	Other Possible Effects
Human Health	Cancer Mortality Non-cancer Effects - neurological - respiratory - reproductive - hematopoietic - developmental - immunological - organ toxicity	
Ecological	Wildlife Plants Ecosystem Biological diversity	Loss of habitat for endangered species
Welfare	Decreases in recreation opportunities, agricultural yields, and visibility	Loss of biological diversity; building deterioration

Source: adapted from Administration Economic Analysis (1998)

Estimates of the impacts upon the atmosphere from GHG-related emission reductions are usually expressed as a percentage or as a measure of per metric tonne of carbon reduced. Complainville and Martins (1994) estimate that reductions in CO_2 from the 1990 baseline of between 4-21% will result in corresponding reductions in SO_X and NO_X of between 4-29% and 3-32% respectively. Scheraga and Leary (1994) present somewhat more modest estimates for the U.S., where a reduction of 8.6% in CO_2 using a carbon tax would generate the following reductions in other pollutants: SO_X (1.9%), NO_X (6.6%), CO (1.5%), TSP (1.8%), and VOCs (1.4%).

Estimates of GHG-related emission reductions can also be significantly influenced by the assumptions adopted. In many U.S. studies, for example, estimates of SO_2 emissions from reductions in GHGs are largely dependent upon expectations of reductions through other policy measures, such as Title IV of the 1990 Clean Air Act (Burtraw and Toman, 1997). Estimates of emission reductions may also be influenced by assumptions on emission rates. There can be significant differences in the estimates of emission reductions depending upon assumptions on emission rates and sources, which is often regionally variable. Actions to reduce GHG emissions from stationary sources such as coal-fired plants or heavy industry can generate considerably higher levels of SO_2 emission reductions (20 kg reduction per 1,000 kg of carbon) relative to mobile sources (0.5 kg reduction per 1,000 kg of carbon) such as automobiles and diesel trucks (IUCC, 1993).

Despite the appearance of relatively small improvements in emissions of GHG-related pollutants, it is important to note that even small amounts can generate avoided damage estimates from ten to several hundred times larger than those for CO_2 (CGCP, 1998). In their review of co-benefit studies for the Intergovernmental Panel on Climate Change (IPCC), Pearce *et al*. (1996) discovered that the value of avoided damages range from US$2 to US$500 per tonne of carbon reduced. On average, the value of co-benefits offsets 30% of the initial abatement costs of GHG emission reductions, although in some cases savings could be much higher (Burtraw and Toman, 1997; Pearce *et al*., 1996). It has been estimated that co-benefits could offset between 30-50% of the initial abatement costs in Norway (Alfsen *et al*., 1992), and over 100% in the UK (Barker, 1993) and Japan (Amano, 1994).

Estimates for Canada are relatively few, limited in scope, and cursory at best, yet they clearly substantiate the view that similar levels of co-benefits are also possible. The Forecast Working Group of the National Air Issues Coordinating Committee (NAICC) developed estimates of reductions in fossil fuel related emissions that would occur as a result of implementing different packages of GHG reduction measures. They estimated that for every 1,000 tonnes of CO_2 emissions reduced in Canada, there would be a corresponding reduction of: SO_2 emissions of between 0.85-1.30 tonnes, NO_X emissions of 0.75-1.55 tonnes, and VOC emissions of 0.40 - 1.40 tonnes (Forecast Working Group, 1995). Another study for the CGCP estimates a much wider range, suggesting that reductions of between 0.4 to 14.5 tonnes for SO_2, 1.3 to 6.6 tonnes for NO_X, and - 4.4 to 0.2 tonnes for VOCs are possible (Haites, 1996).[1]

Model simulations for the 1995 Climate Action Network GHG management plan estimated that a 147 MT reduction of CO_2 by 2010 (approximately 6.5% below 1990 levels) would result in emission reductions of 376 kilotonnes of SO_2 (24%), 281 kilotonnes of NO_X (16%), and 135 kilotonnes of VOCs (13%) (Comeau, 1998). The estimates from this study suggests that achieving GHG emission reductions comparable to Canada's commitment under the Kyoto Protocol would only provide modest reductions in emission of other pollutants, at least relative to the levels that would be required to meet air quality objectives. These results also suggest that it may be difficult to address multiple goals with actions designed to address a single issue (Barclay, 1998b).

None of these studies have attempted to apply dose-response functions to determine impacts upon ecosystems or effects upon environmental, social or human health. Consequently, the co-benefits that may result from GHG-related emission reductions have not been valued in these studies. This represents a rather large knowledge gap in our understanding of co-benefits in Canada, and makes economic analyses of GHG control strategies difficult (Haites, 1996). The treatment of GHG emission reduction options is also variable, underscoring an additional important knowledge gap. While these studies illustrate that emission reductions are highly dependent upon the actions chosen, their own proposed "practical and affordable" actions may actually underestimate the level of reductions possible. For example, in the actions to reduce GHG emissions proposed by Comeau (1998) and Hornung *et al.* (1998), there is no attempt to replace existing coal-fired electricity in Ontario with cleaner and less carbon intensive fossil fuels (e.g. natural gas), nor displace significant quantities of gasoline for motive transport. In the latter case, greater utilization of public transit may result in even larger reductions of GHG emissions, especially in the Greater Toronto Area (Roberts, 1998). Undertaking such actions would likely provide greater reductions in combustion related emissions and provide much greater benefits than a less targeted set of actions (Barclay, 1998b).

3.2 Research response

In response to the importance of having a thorough understanding of the co-benefits associated with GHG-related emission reductions, as well as the need to address the extensive knowledge gaps for the Canadian situation, three analytic activities are currently underway or being proposed as part of the climate change national implementation strategy. Although none of these activities by themselves can provide all of the answers regarding uncertainties surrounding co-benefits, collectively the information they yield may be greater than the sum of their individual parts.

These activities are:

(i) a quantitative modelling exercise to estimate the value of co-benefits from GHG-related emission reductions involving the cooperation and collaboration of various departments within the Federal Government;

(ii) a set of guidelines provided by the AMG to assist the Issues Tables in developing and analyzing possible measures; and

(iii) this overview scoping paper, which provides a science assessment of the current state-of-knowledge, describes a framework assessment for evaluating co-benefits from actions to reduce GHG-related emission, and outlines future research activities that are complimentary to those noted above.

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[1] A shift to natural gas may cause small increases in VOC emissions.

Collectively, these activities will further assist the Issues Tables in their efforts to identify, assess and recommend effective actions to reduce GHG emissions.

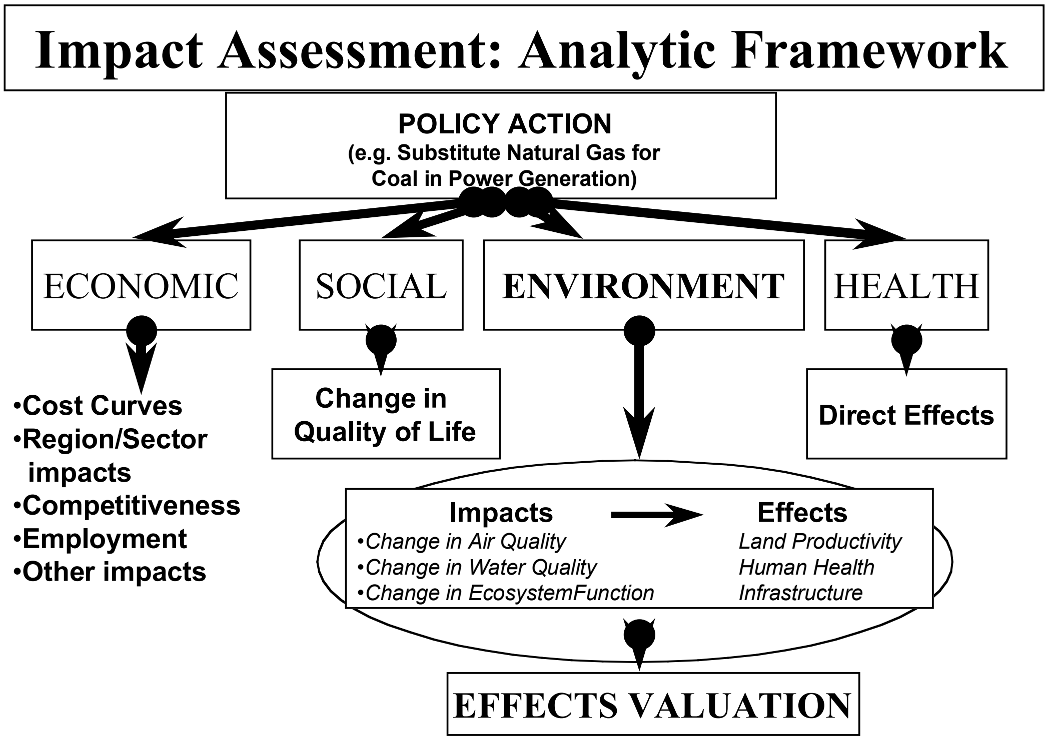
Quantitative Modelling

The quantitative modelling exercise involves a multi-tiered set of 5 distinct but interconnected activities (Fig. 3.1), beginning with the development of a comprehensive emissions database and culminating in valuation estimates of avoided environmental and health impacts. Modelling activities include:

- the integration of the GHG emission inventory into the national criteria air contaminant emissions inventory database system (RDISII), which is used by Environment Canada for monitoring criteria air contaminants, ammonia, and selected heavy metals and persistent organic pollutants;
- the augmentation of the AERCo$t model and database to include GHG emission reduction strategies, and to incorporate quantitative estimates of the cross-pollutant impacts associated with these strategies;
- the inclusion of future GHG emission reductions and Criteria Air Contaminants reductions into Environment Canada's Emissions Forecasting Model (EFM);
- the modification of the Unified Model for Air Quality to quantify the impact on local and regional air quality of measures chosen for Canada's National Implementation Plan on Climate Change; and
- an assessment of the benefits of reductions in conventional air pollutants arising from GHG emission reduction initiatives using the Air Quality Valuation Model (AQVM) (Barclay, 1998a).

In the last stage, the endpoints for the AQVM are primarily measures of human health effects, although

Figure 3.1 An integrated model to estimate the co-benefits of GHG-related emission reductions (Barclay, 1998a)



non-health estimates may include agricultural crop damage, material soiling, material damage, visibility and recreational fishing.

Strategic Environmental Assessment

There are various methods of assessment that decision makers may use to make judgments regarding whether individual actions should proceed as planned, such as undertaking environmental (EIA), social (SIA) and health (HIA) impact assessments. When applied more broadly to evaluate proposed policies, plans and programmes, the process is referred to as strategic environmental assessment (SEA). The ultimate objective of SEA is to:

> systematically integrate environmental considerations into government planning and decision-making processes relating to proposed policies, plans and programs (Hazell and Benevides, 1998; p. 350).

SEA offers a more comprehensive approach to evaluating the cumulative impacts and effects of numerous individual projects, linkages to other policies, and sustainability issues than project based assessments. In recent years, SEA has been gaining wider acceptance and even legal status in many countries, including Denmark, Hong Kong, Norway, Australia and the United Kingdom (BMA, 1998). In Canada, SEA has not been granted legal status; however, it has been used effectively to assess agricultural policies (Hazell and Benevides, 1998). Shillington *et al*. (1997) have proposed that SEA would be a useful tool for helping decision makers address global change and sustainable development, and climate change in particular.

Although a SEA of mitigation actions has not been undertaken, the Issues Tables have been asked to carry out a preparatory assessment of the co-benefits that may occur from their proposed policy options. The approach will consist of a brief environmental scan of all policy options, and a more thorough assessment of the potential environmental effects for policies that are developed more fully as proposals within the Issues Tables' Options Papers. The areas to be assessed include impacts upon the atmospheric, aquatic and terrestrial environments, and the related effects of these environmental changes on social conditions and human health (Table 3.2).

Table 3.2 Key environmental issues suggested by the AMG guide for the assessment of climate change measures

Atmospheric Environment:
1. changes in atmospheric characteristics;
2. changes in air quality as a result of emissions from point- and non-point sources;
3. changes in long-range air pollution patterns;

Aquatic Environment:
1. changes in surface water quality and/or quantity;
2. changes in groundwater quality and/or quantity;
3. changes in oceans quality;
4. changes in aquatic ecosystems/biodiversity;

Terrestrial Environment:
1. changes in soils quantity and/or quality;
2. changes in forestry;
3. changes in terrestrial ecosystems/biodiversity;
4. changes in land use patterns and practices;

Social and Human Health Conditions:
1. changes in perceptions of the quality of life or well-being at the population or community level;
2. changes in human health risk;
3. changes in income or social status;
4. effects on cultural values;
5. changes in population demographics/distribution;
6. changes in work conditions;
7. changes in recreational patterns;
8. effects on cultural and heritage resources;
9. changes in aesthetics.

Source: Barclay, 1998b.

Overview Scoping Paper

The third analytical activity is an overview scoping paper that provides a qualitative assessment of our current state-of-knowledge regarding the co-benefits issue. This involves a preliminary assessment of the relative magnitude of the impacts and effects from GHG-related emission reductions. Impacts refer to changes in pollutants contributing to atmospheric issues other than climate change, in addition to changes in aquatic and terrestrial ecosystems. Effects refer to avoided damages for environmental (agriculture and forestry), social and human health, including co-benefits that may result from the actions themselves to reduce GHG-related emissions. In the latter case, this involves assessing benefits that are non-emission related. A pathway forward is also presented, proposing to establish a science panel and conduct an assessment of co-benefits at the national and regional scale using expert judgement.

Given the enormity of the problem and the extensive literature on the subject, this paper is not intended to be a comprehensive assessment of impacts and effects, but rather should be viewed as an overview of the complex processes, interactions and uncertainties which characterize the issue. Nonetheless, some of the information uncovered in this exercise may be useful as input to the quantitative modelling initiative. The paper can be used as a reference "library" to assist the Issues Tables in their checklist assessment of proposed actions vis-‡-vis the benefits from GHG-related emission reductions. It also serves to illustrate the immense challenge of assessing co-benefits from an integrative perspective, and the complex processes involved. As such, it underscores the need to recognize the vast range of benefits that are possible, many of which are never addressed in the co-benefits literature.

The literature search scanned four bodies of scholarship:

i. studies which directly assessed co-benefits;

ii. environmental assessments of specific atmospheric issues or pollutants conducted separately from climate change;

iii. analyses which considered the impacts and effects from multiple atmospheric issues; and

iv. studies which addressed the externalities of benefits and costs from actions that are not directly attributable to GHG-related emissions.

In the absence of a definitive study dealing directly with co-benefits in Canada, if not elsewhere, the broadening of the literature search enabled insights to be drawn on the current baseline of impacts and effects, including costs, from atmospheric issues other than climate change. Based on other environmental assessments, benefits from reducing emissions of criteria air pollutants could be identified, and transposed to the GHG-related emission reduction context. Further, it might be possible to identify thresholds or critical loads that may be important in achieving meaningful benefits from emission reductions.

In this paper, areas of uncertainty and important knowledge gaps are identified, but it is important to note that any qualitative assessment of impacts and effects based solely upon a literature review will also be subject to uncertainties. The studies reviewed were drawn from an extensive literature, with analyses of benefits from emission reductions occurring in several different countries and regions, many of which present very different atmospheric, environmental and human population conditions compared to those existing in Canada. Consequently, there is an inherent danger in the transferability of data, and comparisons must be treated with caution. At best, the relative magnitude of avoided impacts and effects can be determined from this exercise, rather than a series of estimates that more definitively reflect the benefits that will occur in Canada. A more comprehensive and integrated assessment requires the input from a wide range of science experts, with expertise in the atmosphere, ecosystems, environment, social welfare, and human health.

Co-benefits assessment framework

In developing a framework to assess the relative magnitude of impacts and effects from GHG-related emission reductions, we begin by extending the basic approach adopted in other co-benefits research to include a wider range of pollutants and atmospheric issues that can be found elsewhere in the literature. The assessment framework (Fig. 3.2), and the discussion that follows (sections 4, 5 and 6) underscore the importance of broadening our understanding of co-benefits, especially from an integrative perspective. This involves extending the range of pollutants considered beyond criteria or conventional pollutants, and including toxics and heavy metals in the assessment. Many of these pollutants have undergone scientific scrutiny, leading to a wide suite of policies that have been implemented at various spatial scales to regulate their emissions. The success or failures of these policies to reduce other air pollutants will influence the co-benefits that will be generated through GHG emission reductions; hence it is important to situate the Kyoto Protocol within this broader policy environment.

The impacts of emission upon the whole atmosphere are considered in this framework, including any feedback or synergistic linkages that can occur. The range of impacts also includes both aquatic and terrestrial ecosystems. The range of effects (areas shaded gray in Fig. 3.2) are extended beyond human health, and consider more carefully benefits for the environment and social welfare. In terms of the environment, effects on both agriculture and forestry are considered.

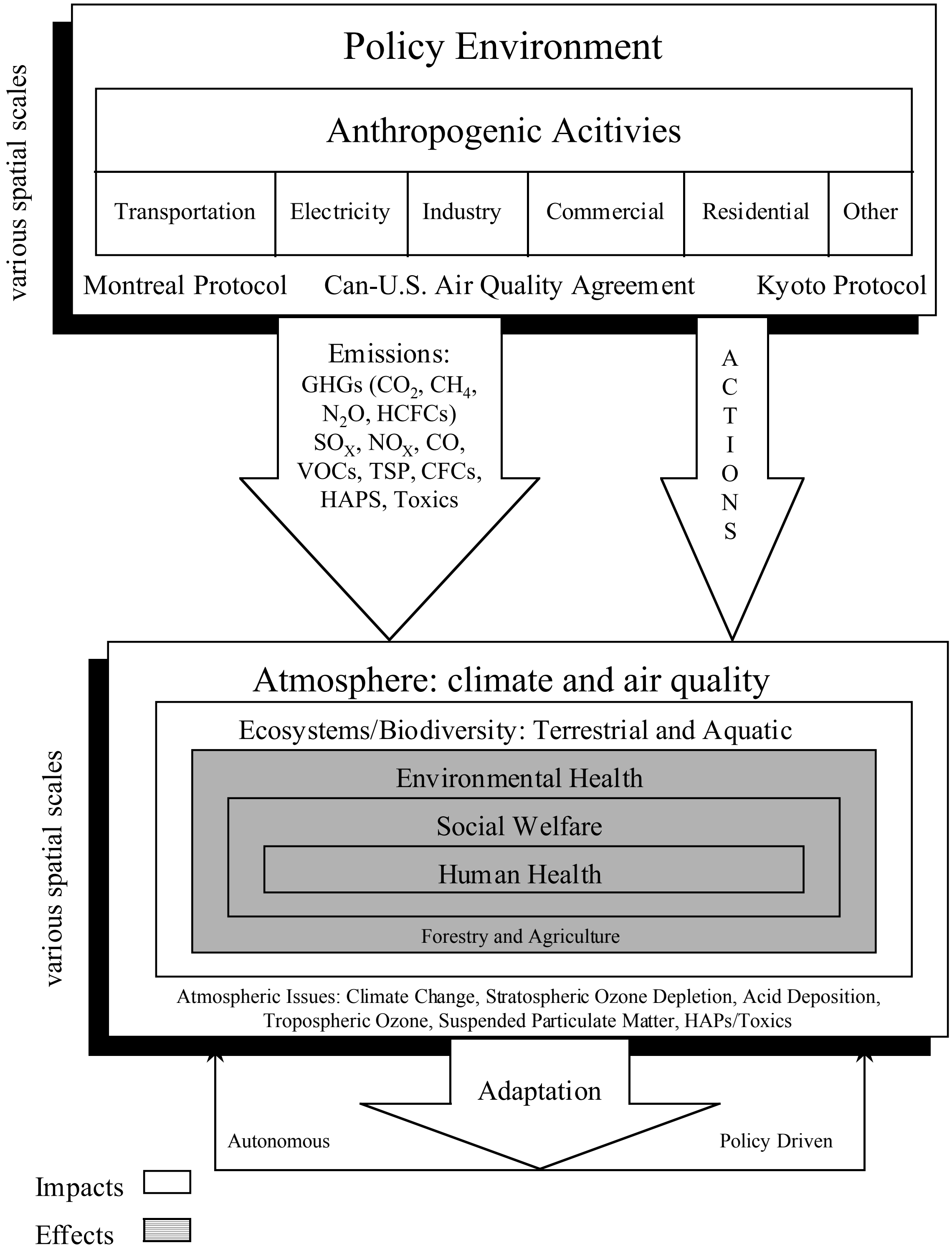
Perhaps the most significant aspect of developing a broader assessment framework involves the interactions between pollutants and atmospheric issues, and the resulting impacts and effects. By considering multiple stresses, there is potential for additive, synergistic and sometimes even counteractive outcomes to occur. Both natural and human systems are complex, and typically do not function in a linear manner (Hansell *et al*., 1997), especially when atmospheric stresses are involved. Atmospheric processes need to be considered, especially transport mechanisms, chemical reactions and meteorological influences upon pollutants and atmospheric issues. Some atmospheric issues such as UV-B and ground level ozone may combine to affect ecosystems or agriculture above and beyond the sum of the individual parts. Similarly, the combination of ground-level ozone and particulate matter ($PM_{2.5}$) may have an even more pronounced effect upon human health, than if measured separately.

Consideration of impacts and effects from actions to reduce GHG-related emissions also requires consideration of a vast body of literature that examines a wide range of externalities associated with fossil fuel combustion. In general, externalities refer to the impacts that affect those that are not targeted by a project or activity. While the broader literature considers impacts and effects from air quality and climate change as externalities in environmental assessments of anthropogenic activities, in the co-benefits assessment framework externalities refer to those that are not directly related to emissions, air quality and other atmospheric issues. Depending upon the anthropogenic activity, externalities include a wide range of impacts and effects. Modal shifts in transportation from motor vehicles to bicycles may improve human health through increased exercise, while electricity generation from non GHG-related emitting power sources (e.g. hydro, nuclear and even solar power) produce impacts and effects upon ecosystems, environment, social welfare and human health. Much of this literature has been ignored in assessments of co-benefits, even though studies of the costs and benefits associated with transportation (Greene *et al*., 1997; Bein, 1997) and electricity (Ottinger *et al*., 1991) suggest that externality effects can be both extensive and substantial.

Adding to the complexity of evaluating externalities is another body of literature which focuses upon “life-cycle assessments” (LCA). Although, it is still a rather young discipline and in need of further methodological development, LCA is a tool that is gaining favor in Western Europe (Gielen *et al*., 1998). It can be used to evaluate the potential environmental effects that the life-cycle of any product or services places upon the global environment (BMA, 1998). In this “cradle-to-grave” approach, both inputs (energy and materials) and outputs (emissions to land, air and water) to a system are considered, generated during materials production, product assembly, product use and waste handling.

Undoubtedly, an assessment of externalities that are not related to atmospheric issues warrants much greater attention than what is possible in this overview scoping paper. However, to illustrate the types of externality effects that could occur and the complexity of addressing impacts and effects external to actions that reduce GHG-related emissions, externalities associated with electricity, transportation and residential energy efficiency are highlighted.

Figure 3.2 A co-benefits assessment framework



4.0 THE IMPACT OF GREENHOUSE GAS EMISSION REDUCTIONS ON ATMOSPHERIC POLLUTION AND ECOSYSTEMS

As mentioned above greenhouse gas (GHG) emissions, especially those from fossil fuels, are closely linked to other air pollutants such as O_3, CO, SO_2, NO_2, PM_{10}, $PM_{2.5}$, sulphates, heavy metals, complex organic compounds, and radioactive material. In Canada, fossil fuel use accounts for about 55% of SO_2, 90% of NO_X, 55% of volatile organic compounds (VOC) and 90% of carbon monoxide emissions (SOE, 1996). Reducing GHG by lowering fossil fuel use will also reduce these pollutants.

GHG concentrations, atmospheric trends, sources and sinks are summarized in Table 4.1. With the exception of CO and methyl chloroform the trend of these trace gases is on the rise. The trend is important, but so is their lifetime. The more stable the compound the longer it will remain in the atmosphere, such is the case of CF_4 whose lifetime is 50,000 years.

In order to assess the benefits of GHG reductions on air quality, we must first evaluate how well Canada is at present meeting all other air quality objectives as atmospheric issues overlap in complex ways. The complexity of the interactions among air issues is expanded on in the MacIver and Urquizo (1999) paper. What follows is a brief explanation of how air issues interact with each other in complex and synergistic ways. Here the focus is on the related impacts of individual pollutants and how they will be affected by GHG emission reductions.

Control of greenhouse gases will have a definite net impact and reductions are expected in:

- particulate matter
- ground-level ozone
- acid rain on aquatic ecosystems and forest ecosystems
- toxic pollutants
- UV-B levels
- carbon monoxide

It should be noted that the benefits are not stated quantitatively but in a qualitative form. Monetary values are not attached to any of the benefits.

4.1 Formal Commitments

Reduction in Emissions of Sulphur Dioxide

The Air Quality Agreement between the USA and Canada has been successful and in this way has set an important precedent for international cooperation on air issues. Under this agreement reductions of SO_2 emissions were set at 40% from 1980 levels and were surpassed by 18% in Canada and by 23% in the US. Nonetheless, current damage to sensitive ecosystems necessitates new reduction targets for post-2000. The Canadian Acidifying Emissions Task Group called for a 75% reduction in SO_2 emissions beyond current commitments (Government of Canada, 1998a). At the present, the two countries have only agreed on a 50% SO_2 reduction target from 1997 levels for the year 2010.

Reduction in Emissions of Nitrogen Oxides

By the year 2010, NO_X emissions are projected to decline 10% from 1990 levels in Canada, mainly as a result of improvements in the transportation sector. The USA is also taking steps to reduce NO_X emissions from both the stationary and mobile sectors in order to reduce acid rain and ground-level ozone. Under the Acid Rain Program a number of utility units in the USA have achieved 16% over-compliance to the required emission rate levels in 1997 (Government of Canada, 1998a).

Reductions in Ground-Level Ozone

The Federal Smog Management Plan provides corrective measures for ground-level ozone and particulate matter in phase II. Phase I set ground-level ozone at 82 ppb over a one-hour period. This objective does not ensure adequate protection to human, animal health

TABLE 4.1 Summary of Important Trace Gases with Increasing Surface Emissions

Gas	Common Name	Surface Concentrations	Atmospheric trend year-1	Atmospheric lifetime year	Sinks	Primary man-made sources
CO_2	Carbon dioxide	358 ppmv	0.4% (1.5 ppmv/yr)	50 - 200[1]	Plants, ocean surface, atmosphere	Fossil fuels burning; and use conservation
CH_4	Methane	1.720ppbv	10 ppbv/yr 0.6%/yr	~9	OH, HO_2 radicals, emoval by soils, atmospheric increase	Domestic animals, rice paddies, biomass burning, gas and mining leaks, wetlands, termites, oceans, freshwater, CH_4 hydrate
CO	Carbon monoxide	35-220 ppbv	- 6.1 to 11% (2 ppb/yr)	~2 months	OH	Combustion of fossil fuels agriculture (oxidation of methane and non-methane hydrocarbons), biomass burning
N_2O	Nitrous oxide	312 ppbv	0.8 ppbv/yr	120	Removal by soils, photolysisin the stratosphere, atmospheric increase	Fossil fuel burning; biomass burning
NOx ($NO+NO_2$)	Reactive odd oxides of nitrogen	10-200 pptv	Unknown	Days		Chemical industry
$CFCl_3$	CFC-11	268 pptv	Leveled off	50 - 55	Photo-dissociation in the mid-to-upper stratosphere	Chemical industry
CF_2Cl_2	CFC-12	500 pptv	Leveling	116	Ditto	Chemical industry
$C_2Cl_3F_3$	CFC-113	82 pptv	Leveled off	~90	Ditto	Chemical industry
CH_3CCl_3	Methyl chloroform	160 pptv	-14 ppt (-2.2%)	4.8 - 5.1	Photolysis, reaction with $O(^1D)$, and removal by lightning	Chemical industry
HCFC	Hydrochlorofluorocarbon	10 pptv	1.67%		Ditto	Substitute for CFC in Chemical industry
HCFC-22	CFC substitute	110 pptv	5 pptv/yr (5%/yr)	12	OH, sea water Refrigeration industry	
CF_4	A perfluorocarbon	72 pptv	1.2 pptv/yr (2%/yr)	50,000	Unknown	Chemical industry
CF_2CLB	Ha-1211r	2.5 pptv	0.1 pptv/yr (3%/yr)	20		Fire extinguisher
CF_3Br	Ha-1301	2.0 pptv	0.3 pptv/yr (8%/yr)	65 - 77		Agriculture, biomass burning, industrial sources, gasoline engine exhaust
SO_2	Sulfur dioxide	10-200 pptv	Unknown	~0.02	OH	Coal and petroleum burning
COS	Carbonyl sulfide	500 pptv	<3	2 - 2.5		Biomass burning; fossil fuel burning

Sources: Krupa and Keckert (1989), Prinn (1994), Environment Canada (1998), Houghton *et al.* (1996), Prinn et al. (1995), Dlugokencky *et al.* (1998), Novelli *et al.* (1998).

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[1] No single life time can be define because of the different rate of uptakes by different sink processes

or vegetation. Both ground-level ozone and particulate matter need to be addressed as an integrated part of an air quality management program. Phase II aims at emission reductions of about 47 ktonnes of NO_X and 183 ktonnes of VOC by 2010 (Government of Canada, 1997). These figures are very modest but this plan sets the ground for an international agreement with the USA.

The Joint Plan of Action for Addressing Transboundary Air Pollution developed in 1997 focuses on ground-level ozone and particulate matter. This plan of action recognizes that USA sources account for 50-60% of the ozone measured in southwestern Ontario during cloud free days (Environment Canada, 1996). Canada's objectives for ground-level ozone and particulate matter (PM) have been under review. The Canadian council of Ministers of the Environment have recently agreed to manage both substances through the development of Canada Wide Standards (CWS) as opposed to the National Ambient Air Quality Objectives. The CWSs are expected to be announced in the fall of 1999.

At present there are no national objectives for PM_{10} nor $PM_{2.5}$. The Federal-Provincial Working Group recommends 25-40 µmg/m^3 for particles under 10 micrometer (µm) or PM_{10} and 15-25 µmg/m^3 for fine particles (< 2.5 µm or $PM_{2.5}$). The USA is phasing out its ozone objective of 120 µmg/m^3 for 24 hours and replacing it with 80 µmg/m^3 for 8 hours. A new standard for $PM_{2.5}$ was set at 15 µmg/m^3 annually and of 65 µmg/m^3 for 24 hours. The PM_{10} standard remains unchanged at 50 µmg/m^3 annually and 150 µmg/m^3 for 24 hours (USEPA, 1997). Negotiations on ozone and transboundary inhalable fine particles were extended to April 1999. With these new ground-level ozone objectives in place the USEPA predicts NO_X emissions to drop below those achieved by the Acid Rain Program and Mobile Source Control programs in the year 2007 (Government of Canada, 1998b).

Reductions in Air Toxic Substances

The Protocols on Persistent Organic Pollutants (POPs) and Heavy Metals aim to cut emissions from industrial sources, combustion processes and waste incineration. This agreement was signed in June 1998 as part of the bilateral Canada-USA Air Quality Agreement.

The Great Lakes Binational Toxics Strategy (Canada-USA Strategy for the Virtual Elimination of Persistent Toxic Substances in the Great Lakes) commits Canada to reduce its mercury emissions and alkyllead in the Great Lakes basin by 90% by the year 2000. The USA is bound to reduce releases of mercury by 50% and the deliberate use of mercury by 50% by the year 2006 (Environment Canada and USEPA, 1997). Under the same agreement Canada is expected to reduce emissions of dioxins, furans, hexachlorobenzenes (HCB), and benzo(a)pyrene (B(a)P) by 90% by the year 2000 in the Great Lakes basin. The USA has promised a 75% reduction in total releases of these pollutants by the year 2006. The Great Lakes Binational Toxic Strategy applies to the aggregate of releases to air and water, but the agreement does not cover the Long-Range Transport (LRT) of air pollutants, which has a huge impact on the Great Lakes.

Predictive computer modeling shows that even if all the agreements outlined above are fully implemented, Canada will still be faced with pollution problems in many parts of the country. The addition of a GHG reduction plan will contribute substantially to the reduction of many of the individual pollutants for which there are already protocols in place. A well thought out GHG reduction plan will benefit the atmosphere, aquatic and terrestrial ecosystems.

4.2 GHG Reduction Benefits to Ambient Particulate Matter

There is “no safe level” for ambient particulate matter (The Federal-Provincial Working Group, 1999). The Canada-USA Transboundary Air Pollution agreement fails to completely eliminate ambient particulate matter. Nevertheless, this new plan will reduce episodic events that at the present range from 100-180 $\mu g/m^3$ for PM_{10}. It will also reduce $PM_{2.5}$ in cities across Canada where average concentrations range from 20-30 $\mu g/m^3$.

Levels of fine particulate matter, which are closely linked to fossil fuel burning, and thus with GHG, will also be reduced. This will mean that NO_X emissions, which in the presence of moisture turn into nitrates, will be reduced by a larger percentage than expected from Phase II of the Federal Smog Management Plan. Targets had been set for a 27% reduction in the Windsor-Quebec City corridor and 19% in the Vancouver area by the year 2010 (Government of Canada, 1997).

However, it is worth noting that the largest anthropogenic source of ambient particulate matter for both PM_{10} and $PM_{2.5}$ is unpaved roads. Unpaved roads are responsible for 2,020 and 300 ktones of PM_{10} and $PM_{2.5}$ compared to 706 and 585 ktonnes from forest fires and 137 and 131 from residential fuel wood combustion respectively (Environment Canada, 1998). These particles are not likely to have climatic repercussions as their sources are localized and their upward distribution in the atmosphere is limited (Leaitch, 1999). Instead, they may have compensating effects on the neutralizing phase of acidifying compounds, - but the extent of this compensation has yet to be established. The sectors that both contribute ambient particulate matter and are linked to GHG are residential fuel wood combustion, the paper and wood industry, and heavy-duty diesel vehicles.

Reducing GHG are thus expected to correlate to actual anthropogenic contributions of particulate matter as explained in the health benefits section. The provinces most likely to benefit are Alberta, Ontario, Quebec, British Columbia, and Saskatchewan, which are among the major contributors for both fine and coarse particles. For instance, Quebec may benefit the most from GHG reduction programs. In Quebec, residential fuel wood combustion represents 98% of the total non-industrial fuel combustion of that province (Environment Canada, 1998) an indoor air quality concern. Programs that reduce wood fire burners or make them more efficient would contribute to the air quality in that province.

4.3 GHG Reduction Benefits to Ground-level Ozone

Ground-level ozone is closely linked to episodes of high concentrations of fine particulate matter. It is produced during the oxidation of methane and certain short-lived gases (mainly carbon monoxide, nitrogen oxides and non-methane hydrocarbons (NMHC)). Concentrations in the troposphere have doubled since pre-industrial times, an increase of about 25 ppbv, with a radiative forcing of +0.4 (±0.2) Wm^{-2} (Houghton *et al.*, 1996). The benefits of reducing ground-level ozone are two fold. First, by removing the toxicity of this gas, and second by removing its radiative forcing. Since VOCs and NO_X are the two major ozone precursors, reducing consumption of fossil fuels will reduce ground-level ozone.

The areas most affected in Canada by ground-level ozone are the Windsor-Quebec City corridor (See Fig. 4.1) and the Lower Fraser valley in British Columbia. A large portion of the ground-level ozone and other air pollutants in the Windsor-Quebec City corridor are the result of LRT from the USA. Benefits from the reduction of GHG will therefore be different for these two areas. Ground-level ozone formation results from the photochemical transformations of NO_X and VOCs emitted from both natural and anthropogenic sources. The latter contributed 2,672 ktonnes of VOC in 1995, mostly from industry and transportation i.e. oil and gas industry, and light duty gasoline vehicles (Environment Canada, 1998).

Ozone mixing ratios exceeding 82 ppb

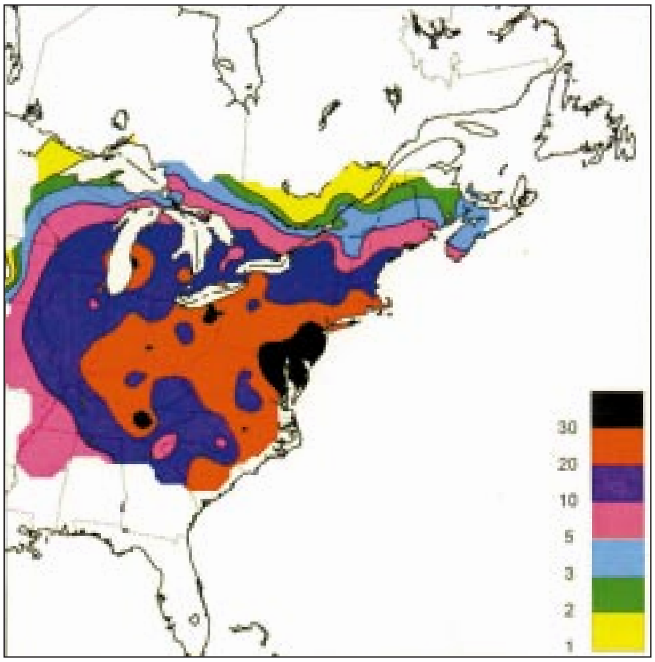

Figure 4.1. Ozone mixing ratios exceeding 82 ppb (Dann and Summers, 1997)

Although VOC emissions from natural sources are 5.5 times those caused from human activities, anthropogenic VOC emissions tend to dominate during ozone episodes (Government of Canada, 1997). High temperatures, which in urban areas further exacerbate this process, lead to greater vapourization of solvents and gasoline, the principal sources of VOCs. Chemical reactions are driven by ultraviolet (UV) radiation in the presence of chemical catalysts, such as hydroxyl radical (OH) and peroxy radical (H_2O_2). Because these reactions are temperature and radiation dependent, ozone episodes tend to be more acute on hot sunny summer days with stagnant high-pressure systems.

Reduced ground-level ozone concentrations would especially benefit vegetation, since plants are more sensitive than humans to ozone stress (Heck *et al., 1*998). Even low concentrations of ozone with intermittent high peaks can cause chronic symptoms in some flora. It would be possible to lessen, or even avoid acute symptoms such as chlorosis, delayed growth, premature senescence and uni- or bifacial necrosis (The Federal-Provincial Working Group, 1998). It may also be possible to reverse or reduce other effects such as the carbon translocation from foliage to the trunk and roots (Cox *et al.*, 1996). In addition, the vulnerability created by shifts in root/shoot biomass ratios could be lessened, thus providing plants with a competitive advantage to withstand drought, fungus, insect attacks, severe winter conditions, or changes in climate.

Ground-level ozone is a powerful toxic gas capable of changing forest composition as observed in the San Bernardino Mountains in California. Sensitive species such as ponderosa and Jeffrey pine were replaced by more tolerant species. This change in structure seriously affects the fire ecology of the area, caused by the large litter – a result of increased needle senescence (USEPA, 1997). Lower levels of ground-level ozone would translate into less flammable material in forest floors and therefore lower fire incidents that may cause the loss of human lives and/or damage to their properties. Considering that forest fires are the largest natural sources of PM_{10} and $PM_{2.5}$, their reduction will be beneficial to most air breathing creatures.

Southern Ontario, the Windsor-Quebec City corridor and areas around the Great Lakes have been identified as having the highest frequency and duration of ozone exceeding the 82 ppb air quality objective. These areas are the most populated in Canada and contain what are widely considered the most productive agricultural lands in the country. The benefits of lower ground-level ozone in agriculture are discussed in detail in section 5. A further benefit of reducing ground-level ozone is protection of endangered species such as the monarch butterfly. The ozone sensitive common milkweed grows in this area, and is the only food source for the monarch butterfly larvae (USEPA, 1997).

4.4 GHG Reduction Benefits to Acid Rain

Particulate matter and ground-level ozone are composed of or are in part the result of NO_X and SO_2. Both of these gases react with water to form sulphuric or nitric acids, the precursors of acid rain. Sulphur dioxide and NO_X are the main precursors of acid rain. Sulphur oxide emissions from anthropogenic sources were estimated at 2,654 ktonnes in 1995 (Environment Canada, 1998). The non-ferrous mining and smelting sector contributes with 33% and the oil industry with 25%. Electric power generation accounts for 20% of SO_X emissions. While Quebec, Ontario, and Alberta have decreased their emissions, Manitoba has increased theirs. In Manitoba, the non-ferrous mining and smelting sector generates 13% of Canada's total, and it represents 98% of the total SO_X emissions for that province.

The other contributor to acid rain is NO_X. An estimated 2,464 ktonnes of NO_X were emitted in Canada in 1995 (Environment Canada, 1998). This amount exceeds the limit of 2,124 ktonnes set in the Protocol Concerning the Control of Emissions of Nitrogen Oxides signed in 1988 (Barclay, 1998a). The four sectors responsible for the majority of emissions (64% of Canada's total NO_X) are heavy-duty and off-road diesel vehicles (24%), upstream oil and gas (13%), all gasoline powered vehicles (17%), and electric power generation (10%). Indeed, transportation accounted for 52% of the total NO_X emissions in 1995 (Environment Canada, 1998).

Although sulphate deposition is still the number one acidifying agent, nitrogen-based acidification is becoming more important in southeastern Canada, particularly in south and central Ontario and southwestern Quebec (Jeffries, 1997). The effects of nitrogen acidification will undermine the ecological benefits expected from sulphur dioxide emission control.

Acid rain is a problem primarily in the eastern part of the country (see Fig. 4.2), an area most affected by LRT (TAETG, 1997). Lakes have been acidified, maple syrup trees showed declining growth, and soil fertility is declining. Although, sulphur dioxide emissions are decreasing (the 1997 emissions in eastern Canada were 54% lower than the 1980 levels), NO_X emissions are increasing. Even after implementing the Post-2000 acid rain agreement, which calls for 50% reductions in SO_2 from 1997 levels, sensitive ecosystems require an additional 25% cut to maintain biodiversity.

Reducing one tonne (1000 kg) of CO_2 eliminates 20 kg of SO_2 and 8 kg of NO_X from stationary sources; and about 0.5 kg and 9 kg of SO_2 and NO_X respectively from mobile sources such as cars (UNEP, 1993). A preliminary calculation using the actions suggested by the Suzuki Foundation (Hornung *et al,* 1998) and the Sierra Club[1] (Comeau, 1998) would result in SO_2 reductions in the range of 2,120–3,678 ktonnes and NO_X reductions in the range of 848–1,471 ktonnes. These amounts, which are based on global estimates provided by the UNEP, are very conservative and fall short when applied to Canada. Canada is the largest consumer of energy per capita in the world (Last *et al.*, 1998). These reductions would benefit the aquatic and terrestrial ecosystems in a myriad of ways as set out below.

Aquatic Ecosystems

The largest impact of acidification is seen in the typically poorly buffered lakes of Newfoundland and southeastern Quebec. These aquatic ecosystems would benefit greatly from reductions of acidic compounds. Lakes in Ontario and southwestern Quebec are generally moderately sensitive.

In fact some of the aquatic effects may be possible to reverse or at least halt. As the pH of the lake water decreases below 6.0, some of these species begin to

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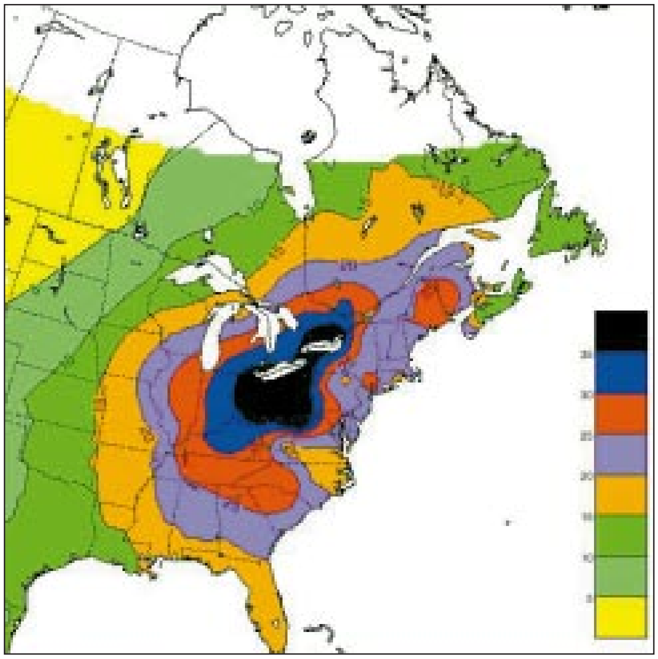
[1] The Sierra Club (1998) and The Suzuki Foundation (1998) suggest reductions of 106 to 183.7 Mt of GHG

Five-year mean excess sulphate wet deposition patterns for 1980-84 and 1991-96 in kg/ha/year

a) Deposition levels 1980-1984



b) Deposition levels 1991-1996

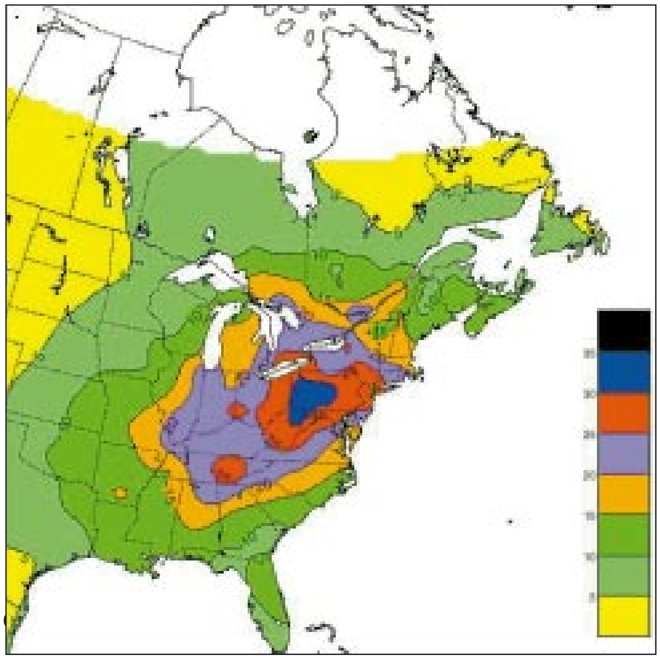


Figure 4.2. Five year mean excess sulphate wet deposition patterns for 1980-84 and 1991-96 in kg/ha/yr (Ro, 1999)

decline. By pH 5.5, some species may disappear entirely, reducing ecosystem biodiversity and altering the food web (Fig. 4.3). By pH 5.0, food webs are seriously impacted and most fish species will have ceased reproducing. Below pH 5.0, some algal species, bacteria and insects dominate the biota. Some of these acid-tolerant algae species (e.g. the filamentous green alga, Zygogonium sp.,) can foul beaches and other littoral habitat (Turner *et al.*, 1995), making recreational use unpleasant and altering natural species assemblages. Other algae species are associated with the production of toxins that may kill fish. With less sulphates and nitrates, the chronic stresses resulting from chemical imbalances could diminish, allowing fish populations and in some cases, biodiversity levels to recover.

Acidification of lakes creates a chain chemical reaction in aquatic ecosystems. Mercury levels in fish are negatively correlated with pH. High levels of mercury are known to have serious effects on wildlife. Low pH in lakes is linked not only to high levels of mercury, but also to high concentrations of cadmium and lead in fish. It is also suspected that low pH in acid sensitive lakes may exacerbate bioaccumulation of cadmium in fish (Scheuhammer, 1996). McNicol *et al.* (1997) believe that low calcium levels allow for increased active and passive transport of mercury across fish gills due to the competitive nature of these two cations. Because mercury has a strong affinity for organic and humic substances, increased loads of organic compounds may be associated with both increased loads of mercury and of methyl mercury - the mercury form most readily accumulated in the tissue of biota. By reducing acidification it is possible to halt the accumulation of toxic compounds in the food web.

The loss of dissolved organic carbon (DOC) in surface waters due to acidification (Fig. 4.4) might also be reversed. Dissolved organic carbon is important in aquatic ecosystems as it acts as a catalyst in the microbial food chain, attenuates solar radiation of all wavelengths including UV-B, decreases the depth of the thermocline, and participates in a number of photochemical reactions (Schindler, 1998). Present UV-B levels have been shown to inhibit both phytoplankton

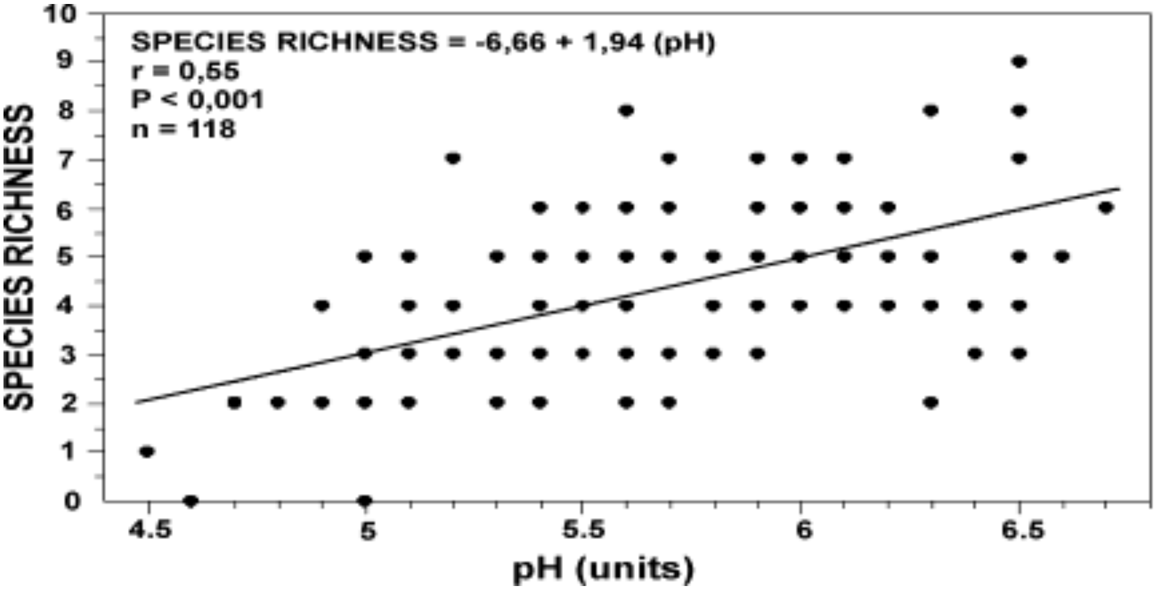


Figure 4.3. Relationship between the number of fish species and pH in 118 lakes from the Outaouais and Abitibi regions of Quebec (Jeffries, 1997)

photosynthesis and growth. In clear oligotrophic lakes, radiation may restrict the habitat available to zooplankton and other aquatic organisms living near the surface.

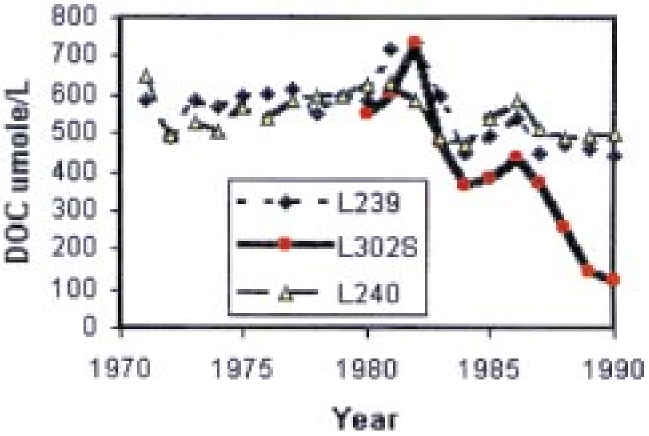


Figure 4.4. Mean annual DOC concentration over time in three lakes at the Experimental Lakes Area (ELA). Lake L302S was acidified from pH 6 to 4.5 (Schindler, 1998)

Reduced acid deposition could actually lead to an improvement of pH levels in lakes of the Atlantic region, which for the last 10 years have not improved (Jeffries, 1997). However, climate change negatively affects recovery. During drought periods, reduced sulphur that has been stored during years of high sulphate deposition is oxidized and released with the first rains, resulting in re-acidification or delayed lake recovery (Bayley *et al.*, 1986). Dillon *et al.* (1997) found a link between drought periods and El Niño events where by following every El Niño event Ontario experienced a drought. The frequency of El Niño events in recent years (Francis and Hengeveld, 1998) might play a role in re-acidification, thus, reinforcing the need to reduce acidifying agents along with GHG.

Greenhouse gas reductions will help reduce SO_2 emissions beyond the 50% target for 2010. This coupled with reductions in NO_X emissions could help meet the critical load criterion (pH 6) in many southeastern Boreal lakes reducing the affected area of ~890,000 hectares and increasing biodiversity. It will also result in a net benefit to approximately 162,000 fish populations from perishing (Jeffries, 1997). Recovery of lakes could be possible, provided that the natural buffering capacity has not been depleted (McCrea and Burrows, 1998).

Forest Ecosystems

It is estimated that 20–30 million hectares of Canada's forests are exposed to sulphate and nitrate deposition, and are bearing (or near to bearing) critical loads in the soil. Acidification of soils reduces seed germination and alters nutrient and heavy metal availability (USEPA, 1997). Despite relatively small changes in pH in some watersheds, large quantities of calcium and magnesium are exported with drainage to a point where the maintenance of soil fertility and forest productivity is endangered (Houle *et al.*, 1997). Soil fertility is rapidly being degraded at the present rate of acid deposition. These impacts, as stated in the 1997 Canadian Acid Rain Assessment, (which will be lessened given a decrease in deposition levels as a result of GHG reductions) are summarized below (Hall *et al.*, 1997).

- Damage to the tree's protective leaf or needle cuticle;
- Decrease net photosynthesis and nutrient uptake; this effect increases with absorption of sulphate;
- Impaired germination of pollen in white birch and mountain paper birch with acid fog or mist, with pH below 5.6;
- Reduced frost hardiness;
- Increased vulnerability to pollution and climatic perturbations;
- Increased aluminum/calcium ratio in woody tissue leading to mortality. The mobilization of aluminum through soil acidification impedes the uptake and transport of base cations such as phosphorus and potassium by the tree (Mahony *et al.*, 1997);
- Contributes to nutrient deficiencies, which are likely to increase tree susceptibility to drought, ice storms and pathogen or insect attacks (Watmough and Hutchinson, 1998).

4.5 GHG Reduction Benefits to Mercury

A recent relationship between mercury and greenhouse gases has been established. It is believed that the same substances that are responsible for ozone depletion are also responsible for the transformation of mercury from the gaseous phase to the particulate phase (Schroeder *et al.*, 1999). Highly reactive chemical species react with and oxidize the normally inert gaseous mercury (consisting mainly of elemental mercury vapour) to one or more compounds of mercury with vapour pressure substantially below that of molecular mercury. The much less volatile compounds, such as mercury halide or oxides, exist in the particulate state. Mercury in particulate form would readily deposit on terrestrial and aquatic ecosystems, thus, entering the pathway of biological methyl mercury, which has the unique ability to bioaccumulate in the food chain. Bioaccumulation can lead to serious neurological damage particularly in fetuses and in young children (Schroeder *et al.*, 1999).

The major sources of atmospheric mercury are fuel combustion, gold mining, chemical production, vehicular and aircraft traffic, and waste incineration. LRT from the Ohio Valley accounts for a large amount of mercury in Canada. This area holds a large number of coal fired electric generating stations. Reducing levels of this toxic pollutant is of interest since evidence suggests that acidification of water bodies enhances mercury accumulation in fish tissues. The acid deposition program may have already caused a reduction in the rate of mercury accumulation in fish and therefore benefited the health of members of the upper echelons of the food chain that eat fish (including humans). Unfortunately, mercury levels in fish are not being monitored on a continuous basis.

Unacceptable levels of mercury in fish have become a pervasive problem. Global atmospheric concentrations of mercury appear to be increasing by about 0.6 to 1.5% per year (Mierle, 1997a). The doubling of mercury in the atmosphere of the Northern Hemisphere may explain the recent increases of mercury at the surface of sediments in lakes remote from point sources and in the Arctic. Climate warming also has an effect on the amount of mercury accumulation. Warm waters promote the formation of methyl mercury, and UB-V and acid rain catalyzes its formation (Schindler, 1999).

GHG reductions will result in less acid deposition and more DOC, thus permitting less UV-B penetration and so reduced bioaccumulation of mercury in fish. The benefits will not only extend to wildlife but to human health. In this regard, southeastern Canada, the area receiving the greatest acid deposition, will be the greatest beneficiary.

Mercury in Wildlife

Mercury, particularly in Ontario, has been found everywhere and seems to increase with fish size. About 80% of the population of large walleye in Ontario contained above 0.5 ppm of mercury, and 10% contain above 1.5 ppm, a concentration well above recommended levels for human consumption (Mierle, 1997b).

More research has been directed to the effects of mercury on humans than in wildlife. Mierle (1997b) puts forth that although the dose-response relationship for wildlife has not yet been established, a number of studies suggest that for most species, levels of between 0.3 to 2.0 ppm in their diet will create toxic effects.

For example, levels of 0.9 ppm of mercury in food were lethal to mink after about three months and caused emaciation in wild loons. Moreover, loon reproduction is impaired when mercury in prey fish exceeds 1 - 2 μg/g (Scheuhammer and Blancher, 1994); this occurs in 5 - 30% of Ontario lakes. At 0.6 ppm, the reproductive success of mallard was halted. Human consumption guidelines do not offer protection to wildlife. McNicol *et al.* (1997) found that lethal and sub-lethal effects of dietary mercury exposure in various birds have been demonstrated at concentrations as low as 1-2 $\mu g\ g^{-1}$ dry weight. Sensitivity differed among species. There have been few studies of mercury in wild mammals. There are reports of decreasing concentration of mercury with age in otter and mink (Evans *et al.*, 1997). Otters less than two years old had higher concentrations of mercury than those between two and six years. Animals older than six had higher concentrations of mercury than the two to six year old group. Older individuals were scarce. One possible interpretation is that only individuals with low mercury levels survive to be older.

4.6 Other Toxic Substances

Greenhouse gas reductions could also have a huge impact on the LRT of air toxic substances, in that the rate of the “grasshopper effect” would be slowed down from what it would be with a global increase in temperature. With the grasshopper effect, toxic substances such as pesticides (which may have been sprayed on fields 50-60 years ago) evaporate with warmer temperatures, are carried on the wind, and then deposited in colder climates. The grasshopper effect is magnified in cold countries such as Canada, since the air toxic substances that have been deposited will not “make another jump”. This is known as the cold distillation effect and accounts for most of the pollution in the Arctic. A number of persistent organic pollutants (POPs) including pesticides like DDT and Toxaphene are found in the Great Lakes, the Rocky Mountains or the Arctic (IADN, 1998). There, they precipitate with snow or rain and become part of streams and lakes only to be absorbed by plants and eventually fish.

Reducing energy consumption will reduce the amount of pollutants emitted by fossil fuel combustion. For example, stationary and mobile sources (e.g. automobiles, trucks) are known to be major contributors of hazardous air pollutants (i.e. benzene and 1,3-butadiene are both CEPA-toxic) (Environment Canada, 1999). Thermal plants emit polycyclic aromatic hydrocarbons (PAHs), heavy metals such as mercury and copper, and radionuclides into the air in trace amounts; they discharge contaminated wastewater and generate contaminated solid wastes (Eaton *et al.*, 1994). Coal generating stations release HCBs. Many GHG emission reductions will be as a result of reductions in fossil fuel combustion, a source of toxic substances such as arsenic, cadmium, chromium, mercury, lead, copper, nickel, fluorine, zinc and polycyclic aromatic hydrocarbons (PAHs).

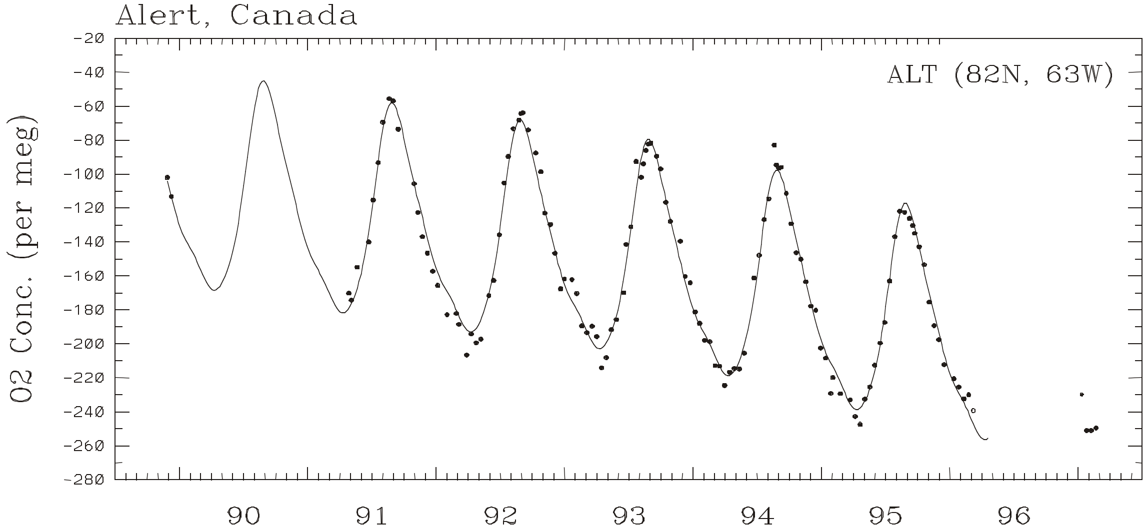


Figure 4.5. Oxygen concentrations expressed as changes in the O_2/N_2 ratio (Keeling *et al.*, 1999)

4.7 Benefits of Reducing CO_2

Reducing GHG will also reduce the oxygen consumption required in the formation of CO_2. Oxygen concentrations have been monitored at Alert, NWT since 1990 and, as seen in Fig. 4.5, there is a downward trend expressed as changes in the O_2/N_2 ratio. Although the downtrend might seem minuscule, Keeling *et al.* (1999) state that “the observations show a large deficit in potential oxygen in the Northern Hemisphere relative to the Southern Hemisphere.” An indefinite increase in CO_2 would unbalance our primary survival element.

The positive effects of CO_2 on vegetation would be enhanced if the adverse effects of acid rain and ground-level ozone are removed. CO_2 is a fertilizer to plants. Plants with 3 carbons as intermediary compound (C_3) in their photosynthetic pathway get bigger with high levels of CO_2 (Fig. 4.6). Yields increase and use water more efficiently. This may prove important since 16 of the major 20 crops are C_3. Furthermore, 14 of the 18 more noxious weeds are C_4 plants, which would be expected not to respond as vigorously as the 16 food crops. However, there is evidence that weeds respond more favourable to CO_2 increase regardless of their photosynthetic pathway. This and a chain of secondary effects complicate the outcome.

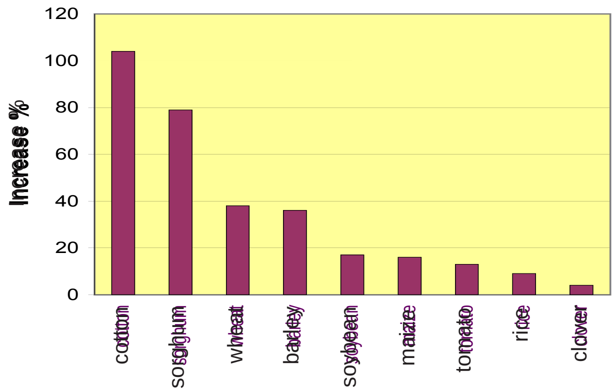


Figure 4.6. Predicted increase in yields of 9 major crops caused by 2 times CO_2 (UNEP/GEMS, 1987)

As a rule of thumb, growth seems to increase by 0.5 to 2.0 % for each 10-ppmv rise in CO_2 (UNEP/GEMS, 1987). Experiments demonstrate that, although biomass increases, the food quality of plants tends to deteriorate as CO_2 levels increase. It has been shown that pests feeding from soybean leaves have to consume more to gain their required nitrogen protein levels. Pests, then, may be more damaging in carbon-rich environments (UNEP/ GEMS, 1987). Elevated CO_2 slows down the decomposition rate resulting in C storage in the soil caused by the limited nitrogen (Wood *et al.*, 1994). This means that nutrient limitations on a global scale would ultimately limit plant response to CO_2 enrichment.

4.8 GHG REDUCTION BENEFITS TO DECREASED UV-B

Stratospheric ozone has been declining at a steady rate of 5% per decade since 1980 (see Fig. 4.7) (Wardle *et al.*, 1997; Oltmans *et al.*, 1998; Tarasick, 1999; Anlauf, 1999). A series of photochemical reactions involving O_3 and molecular oxygen (O_2) occur in the stratosphere. Ozone strongly absorbs solar radiation in the range of 210 to 290 nm, whereas O_2 absorbs radiation at wavelengths less than 200 nm. As the wavelength increases through 280-320 nm, ozone absorption becomes weaker. The absorption of UV (primarily by ozone) is a major factor in the increase in temperature with altitude in the stratosphere. Through a series of chemical reactions, solar radiation breaks apart O_2 to form O_3 and release heat. The flux of photochemical active UV-B photons (wavelength $\leq$ 315 nm) into the troposphere is limited by the amount of stratospheric O_3.

Ozone recovery in the stratosphere will take more or less 150 years. Slowly the present irradiance levels at 300 nm should decrease from an excessive 35% per year in the winter and 6.7% per year in summer in Toronto (Kerr and McElroy, 1993), to what they were before ozone depletion. At the same time, erythemal irradiance[2] (the wavelength most damaging to the skin) is expected to decrease slowly from its present values of +5.3% per year in the winter and +1.9% per year in the summer (Kerr and McElroy, 1993). Some of the following effects will also start reverting:

- UV-B was found to affect photosynthesis, and stomatal resistance to water loss through transpiration and to CO_2 uptake. There is also some evidence that it could affect pollen viability, decrease height growth of seedlings, reduce leaf area growth. Out of 26 trees studied 12 showed decrease in growth; only two showed an increase and 12 showed tolerance for UV-B (Krupa and Kickert, 1989)

- Shallow freshwater ecosystems are particularly vulnerable to enhanced levels of UV-B exhibiting changes in primary productivity, nutrient cycling, community structure, and modification of the transport of toxic chemicals in the food chain. DOC attenuates UV-B in surface waters. Unfortunately, UV-B penetration has increased between 22% and 60% (Wardle *et al.*, 1997) due to acid deposition and climate warming (Schindler *et al.*, 1996).

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[2] Erythemal Irradiance is the UV spectral irradiance multiplied by the McKinley-Diffey action spectrum for erythema (skin burn), integrated and divided by 25 mWm^{-2} (Burrows *et al.*, 1994).

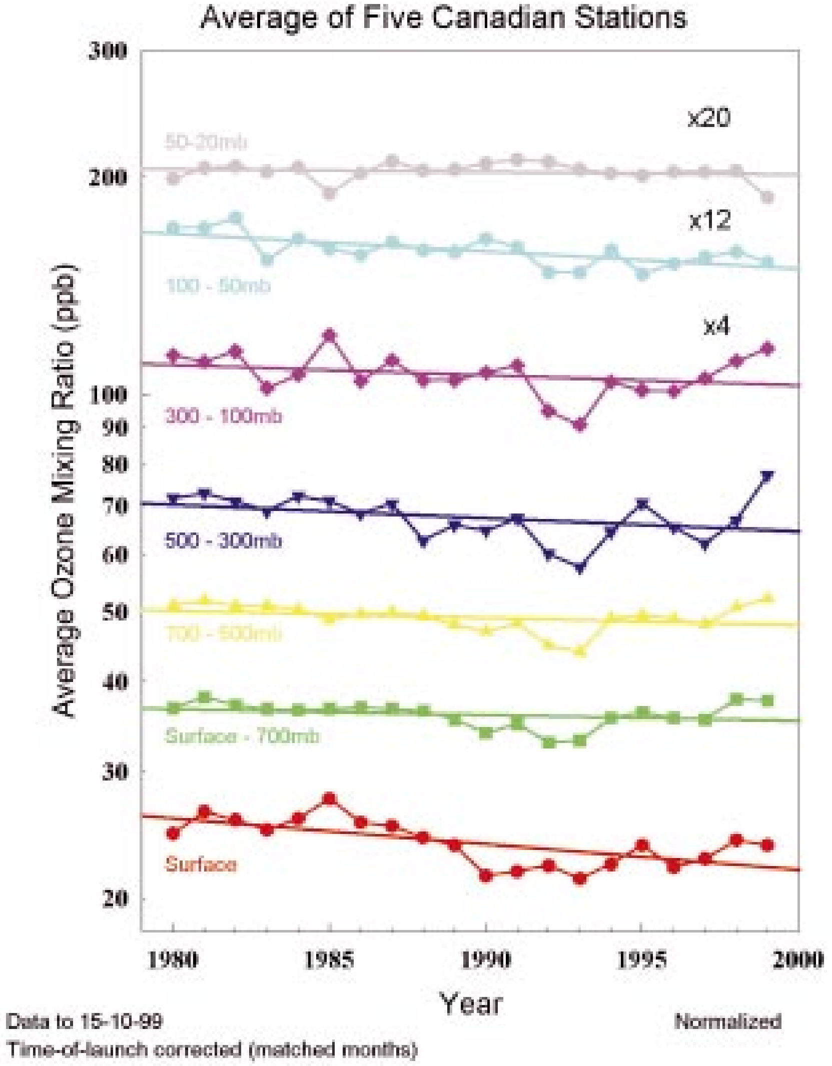

Figure 4.7. Free tropospheric measurements of ozone showing a decline that closely follows the stratospheric decline rate (Tarasick, 1999)

Further effects of increased UV-B radiation (due to ozone depletion) might begin to revert such as:

- increases in skin cancer;
- suppression of the cellular components of the human immune system;
- damages of the membrane surrounding the cell, the chloroplasts and the DNA of plants;
- cataracts;
- other biological defects (Wardle *et al.*, 1997).

Conversely, SO_2 acts as a compensating compound in absorbing UV-B radiation. This has been observed in Japan where the plume of the Kagoshima volcano reduced the UV index by as much as 25% (Wardle *et al.*, 1997). In industrialized regions, where sulphate aerosols are particularly high, the aerosol-induced cooling may account for more than 25% of the warming caused by CO_2 (Rodhe *et al.*, 1995). Science, models and policies towards controlling one and not the other could exacerbate environmental problems.

During the late 1980s it was believed that increasing trends of ground level ozone could compensate for up to 20% of the loss of stratospheric ozone in certain geographical locations (Krupa and Kickert, 1989). This statement has not gained acceptance specially because in certain areas, for instance in Canada the tropospheric ozone rates are decreasing at the same level as the stratospheric ozone (Fig 4.7). Reducing GHG that also act as ozone depleting substances, such as methane (CH_4), nitrous oxide (N_2O), methyl chloride (CH_3Cl), synthetic chlorofluorocarbons (CFCs), chlorocarbons (CCs) and organo bromine (OB) compounds, will prevent further ozone layer destruction.

4.9 GHG REDUCTION BENEFITS OF REDUCED CARBON MONOXIDE

Another benefit of an effective GHG emission reduction plan would be the avoidance of episodes of elevated CO in ambient air. In 1995, an estimated 10,355 ktonnes of CO were emitted to the atmosphere purely from anthropogenic sources (Environment Canada, 1998). This amount is four times greater than either SO_X or NO_X emissions.

Transportation accounted for 65% of all emissions followed by industry with 21% and non-industrial fuel combustion with 10%. The greatest contribution comes from Ontario (31%), followed by Quebec (20%), Alberta (14%) and British Columbia (12%). The light-duty gasoline vehicles were the single largest source sector in every province except Newfoundland, where residential wood-fueled combustion makes up 36%, compared to automobiles 23%.

Carbon monoxide reacts primarily with ozone (O_3), hydroperoxy (HO_2), and hydroxyl radicals (OH). Hydroxyl radicals act as sinks for carbon monoxide 90-95% of the time (Novelli *et al.*, 1998). Reduction of GHG will translate into less CO in the atmosphere. Therefore more OH will be available for reaction with gases such as methane (CH_4) and halogenated CFCs.

Because CO impacts on regional air quality, its reduction will mean less ground-level ozone. In areas with sufficient NO_X ($NO + NO_2$), HO_2 produced from the oxidation of CO initiates photochemical reactions, which will result in net formation of ground level ozone (Novelli *et al.*, 1998).

$$OH + CO \rightarrow H + CO_2$$
$$H + O_2 \rightarrow HO_2$$
$$HO_2 + NO \rightarrow OH + NO_2$$
$$NO_2 + \text{ultraviolet} \rightarrow NO + O$$
$$O + O_2 \rightarrow O_3$$

$$\text{Net effect: } CO + 2O_2 \rightarrow CO_2 + O_3$$

4.10 CONCLUSION

The benefits to air quality of reducing GHG emissions should be seen from a multidisciplinary perspective. As noted above many of the air pollutants are related to each other in intricate ways. Determining the action that will bring the largest gain in terms of GHG reduction should be evaluated against the gains from related air pollutants. In this evaluation one should keep in mind that links are complex and in many cases have yet to be established. At present, estimates of the benefits at the ecosystem level may be undervalued. For example, let us considered the benefits from reduced acid deposition to aquatic and terrestrial ecosystems. The extra SO_2 and NO_X reductions will help save the ~890,000 hectares of lakes, ~162,00 fish populations and 20-30 million hectares of forests presently affected.

The overview presented here is a far cry from what needs to be learned to assess the regional benefits a GHG reduction program. It is apparent that the most obvious gains will be made in acid rain, ambient particulate matter and ground-level ozone. Whereas less gains are expected in global issues such as UV-B and LRT of toxic pollutants. Caution must be taken to avoid double counting the benefits of GHG emission reduction. The gains to be obtained from commitments today must persist.

The commitments to air pollutants, as discussed earlier, are set at different percentages (see Table 4.2). In this Table ground-level ozone, which results from three different compounds VOC, NO_X and CO does not have a set target. With the exception of NO_X within the acid rain program, there have not been set targets for either CO or VOC. The expected reduction of ground-level ozone is then only from GHG emission reductions. In other cases, the increment percentage to be obtained from GHG reduction would fall within the white margin of each bar (i.e. they are additional to current commitments). The overlap of benefits that will occur with earlier commitments would offset costs of reduction, thus the savings should also be accounted in the evaluation. The benefits will vary according to the type of pollutant. For instance, reduction of toxic substances will be minimal in comparison to reducing CO, which does not fall within any other reduction program.

TABLE 4.2 Current commitments on air quality issues

Toxics		90%
APM		23%
O_3	VOC	
	NO_x	
	CO	
NO_x		10%
SO_2		50%

100%

Toxics = Air toxic substances
APM = Ambient Particulate Matter
O_3 = Ground-level ozone

5.0 AN ASSESSMENT OF THE RELATIVE MAGNITUDE OF EFFECTS

Although there are a wide range of estimates regarding the overall magnitude of reducing GHG-related emissions, there is general agreement regarding the areas where these co-benefits will accrue. Benefits for human health, through improvements in air quality, have received the most attention in the literature (Lee Davis *et al.*, 1997), whereas effects upon the environment and social welfare have garnered less consideration. It is perhaps not surprising that the estimated value of the positive effects for human health has dominated most assessments, especially avoided premature deaths from reduced exposure to various forms of particles.

Avoided premature deaths have been estimated to account for about 75-85% of all estimated benefits in economic assessments of improved air quality (Burtraw and Toman, 1997). In comparison, the valuation of reduced mortality consistently exceeds those for various indicators of reduced morbidity. However, there is some question if human health studies capture the full extent of morbidity benefits, especially those that do not involve hospitalization. It is possible that the benefits for morbidity may be significantly greater than the literature suggests, and an adjustment in this area would increase the total value of impacts and effects, in addition to altering their relative magnitude. Furthermore, the value of benefits (or avoided damages) for the environment and social welfare, at least when they are considered, tend to be lower still, by many orders of magnitude.

There are no previous studies that directly assess or value the effects from GHG-related emission reductions in Canada. This knowledge gap raises a fundamental question if the relative magnitude of effects will be much different in Canada, compared to other countries? A review of the broader literature adds to the uncertainty, by suggesting that the relative magnitude of co-benefits from reductions in adverse effects for other sectors in Canada may be greater than previously estimated. This includes reduced adverse effects upon the agricultural and forestry sectors, improvements in social welfare, and positive effects upon human health beyond those solely associated with particulate matter.

The broader literature provides extensive evidence that the adverse effects upon human and natural systems from various pollutants and atmospheric issues can be considerable, both on an individual and integrative basis. By extension, this implies a strong possibility that the value of avoided effects through various environmental, social welfare and human health pathways may be greater than previously estimated. This is certainly the case if the benefits and costs that are not directly related to emissions and air quality are also factored into estimates of co-benefits.

In this chapter a review of the literature is presented in order to produce a preliminary assessment of the relative magnitude of the effects from reductions in GHG-related emissions. As in the case of climate change impacts, there are many uncertainties associated with estimating the effects and value for a wider range of pollutants and atmospheric issues, and for an extended range of damage pathways. There is already considerable debate in the literature regarding the positive effects and their value for human health. In extending our assessment beyond these effects, uncertainties become even more problematic, with increasing potential for synergistic and antagonistic relationships. Notwithstanding these challenges, a qualitative overview of the literature provides many insights regarding the relative magnitude of effects for the environment, social welfare and human health.

5.1 Environmental Effects

Observations of decline in forests and agricultural productivity have led to concern that continuous exposure to a range of pollutants is affecting the health of Canada's environment. In turn, this concern has resulted in the examination of atmospheric stresses for many species of trees and crops. Numerous dose-response analyses have been conducted in controlled exposure systems (e.g. growth chambers), greenhouse or field environments, and it is generally recognized that acid deposition can have a greater effect upon forest productivity than O_3. In contrast, O_3 has been shown to have a greater effect upon agricultural crops than acid deposition. Increasing UV-B may also have an effect upon forests and agriculture, but the research to date has been somewhat limited, exposing a knowledge gap on the long term and interactive effects of this atmospheric stress.

In this section the primary focus is on the effects of acid deposition and O_3. Since UV-B is a global scale problem, it is unlikely that any efforts by Canadians to reduce emissions of pollutants that contribute to stratospheric ozone depletion will generate substantial benefits that are either immediate or local in nature. Neither can reductions in GHG-related emissions by Canada alone be expected to have a significant impact upon stratospheric ozone depletion. Stratospheric ozone depletion and increasing UV-B rays are addressed in terms of how it can interact with other atmospheric stresses to produce an additive effect upon the environment, thereby making reductions in GHG-related emissions even more important.

The vast majority of scientific inquiry on environmental effects tend to focus on what can be referred to as "first order effects", such as tree growth and crop yields. With the exception of the climate change impact literature, there is a void in the literature that extends the analysis into subsequent levels of effects through the economy. Typically referred to as "second order effects", they are even more difficult to quantify, yet they could be substantial. In the case of the environment, second order effects includes benefits for farm families, forestry workers, and the many industries providing inputs and value added processing for these primary activities. While such values are difficult to measure, it is expected that the secondary effects could be substantial, particularly for communities and regions highly dependent upon agriculture, fishing or forestry. Yet the effects and benefits may not stop here, but may extend even further into issues of sustainability and spiritual health. As Hall *et al.* (1997) note,

> the maintenance of forest ecosystem health is essential to the sustainability of Canada's forests and the overall well-being of the country (p. 34).

Indeed, it is difficult to separate the health of the ecosystem from that of the environment, social welfare and human health. The sustainable functioning of environmental, social and economic systems are inextricably tied, and have a direct bearing upon the health of Canadians. Some theological ecologists, for example, have argued for a holistic view of human and ecosystem health, recognizing that the latter has an essential role in providing "the life-giving nourishment of our physical, emotional, aesthetic, moral, and religious existence" (Berry, 1988, p. 81). Although it is difficult, if not impossible, to assign a value to such non-tangible effects, nor account for their interactions, this view illustrates that the extent to which we measure effects is a subjective process. Consequently, the overall value of co-benefits could be significantly greater than that measured conventionally.

Forestry

In a recent assessment of Canada's forests (Hall *et al.*, 1997), it was concluded that acid deposition, especially at levels exceeding critical loads, continue to inflict severe adverse effects upon the health of Canada's forests. If acid deposition continues to exceed critical loads, it will pose a serious threat to the sustainability of forests in Ontario, in addition to large portions of the commercial forest in Quebec, Nova Scotia and New Brunswick. At present, no reliable monetary values regarding the benefits of reducing acid deposition upon Canada's forest industry have been estimated (TAETG, 1997). At the very least, benefits would be comparable to avoided reductions in forest productivity, which is generally accepted to be 10%. If additional benefits are also considered, such as maple syrup production, ecotourism and recreation, then the value of benefits would increase accordingly. Canadian forests also have significant ecological value, providing habitat for wildlife and playing a major role in the carbon cycle of the global climate system.

Neither do these estimates take into account the co-benefits that may occur from reductions in other pollutants, whose adverse effects upon forests have been well documented elsewhere in the literature. For example, increased exposure to O_3 could have significant long term implications regarding the capacity of trees to protect themselves against disease and insect attack (Kelly *et al.*, 1993). Furthermore, in combination with increasing levels of SO_2, O_3 has been shown to significantly depress photosynthesis in Spruce and Fir (Schweizer and Arndt, 1990), whereas the addition of acid deposition to this mix of stresses increases frost sensitivity/injury (Chappelka and Freer-Smith, 1995). As precursors to O_3, reductions in emissions of NO_X and VOCs would increase the value of co-benefits beyond those solely attributed to improvements in acid deposition.

Agriculture

In contrast to forestry, research has shown that agriculture is much more sensitive to O_3 than acid deposition. Prolonged exposure to O_3 can cause significant cellular disturbances, involving changes in both functional and structural characteristics in crops. A wide range of effects can occur, such as foliar pathologies, altered carbohydrate allocation, reduced growth and yields, as well as impacts upon plant communities and ecosystem functioning (RMCC, 1990). Effects are typically measured in terms of changes in photosynthesis, leaf conductance, water use efficiency, leaf area, specific leaf weight, crop maturation weight, flowering, dry matter production and yield, drought stress sensitivity, and mineral stress sensitivity (Krupa and Kickert, 1993). In Canada, several studies have been conducted that assess foliar injury response to ambient O_3 conditions, primarily in British Columbia, Ontario, Quebec and New Brunswick.

Although no one exposure index or dose statistic applies to all crop species, research on the relationship between crop response and O_3 exposure points to the importance of peak concentrations and weighted, cumulative-exposure indices (Multi-stakeholder NO_X/VOC Science Program, 1997; RMCC, 1990). According to the findings of the U.S. Environmental Protection Agency’s National Crop Loss Assessment Network (NCLAN), several plant species exhibit growth and yield effects when mean O_3 concentrations exceed 50 ppb for a 4-6 h/day period for at least two weeks (Pearson, 1997). Of the species and cultivars tested, at least 50% were predicted to exhibit a 10% yield loss at 7-h seasonal mean O_3 concentrations of 50 ppb or less.

The NCLAN has identified seasonal means at or below 35 ppb as the generally accepted minimal yield effect threshold. The achievement of this standard, however, would not provide complete long-term protection for all sensitive crops (RMCC, 1990; Multi-stakeholder NO_X/VOC Science Program, 1997). Nonetheless, achieving this standard would likely result in significant avoided crop damages, since many rural monitoring sites in Ontario have recorded up to 170 exceedances of the 80 ppb hourly criterion during worst case years for O_3 (e.g. the summer of 1988). Pearson (1989) has estimated the value of increased productivity from attaining this standard for 19 agricultural crops and ornamentals in Ontario to be between \$17 - \$70 million annually. Crops at greatest risk include dry beans, potato, onion, hay, turnip, winter wheat, soybean, spinach, green bean, flue-cured tobacco, tomato and sweet corn. Marginally at risk crops include cucumber, squash, pumpkin, melon, grape, burley tobacco and beet. In comparison, currently there are no identifiable risks to sensitive crops in Alberta, while in the Lower Fraser Valley in British Columbia, \$9 million in losses to elevated O_3 levels has been estimated (RMCC, 1990). In the U.S., agricultural losses to O_3

have been estimated to be between $1 - $3 billion annually (Hale *et al.*, 1997).

Although effects are ultimately determined by pollutant levels and the sensitivity of exposed environments, the effects of O_3 upon agricultural crops grown in Canada may be greater than previously estimated. Krupa and Kickert (1993) identify a number of additional crops that are sensitive to enhanced levels of O_3, including peas, oats, lettuce, alfalfa, radish, clover, cabbage and carnations. Although Runeckles (1984) states that there is sufficient evidence for the occurrence of synergistic effects of SO_2 + NO_2, and SO_2 + O_3 that seriously affect the growth of many crop species, by 1990 field research had not shown significant interactive effects between acid deposition and O_3 (RMCC, 1990). Neither had experiments in the field been able to prove that ambient rain acidity reduced crop yields.

These results, however, must be interpreted with caution, and come with the following caveats:

- dose-response studies have been performed on only a small number of crops species, such as soybeans, beans (snap), clover, corn, oats, potato, radish, rye grass and tobacco;
- for most crops tested, screening experiments have been conducted on only one or two cultivars to determine species sensitivity to rain acidity;
- studies have demonstrated that plant response may not only be species dependent, but also strongly cultivar dependent; and
- perennial crop groups such as fruit trees and forage crops have not been examined adequately (RMCC, 1990; p. 56).

It is widely recognized that environmental conditions, such as drought, may further influence plant response to acid deposition. Moreover, little is known regarding the long-term effects of acid deposition on micronutrient cycling and plant availability in agricultural soils. On the other hand, most agricultural soils in Canada have a relatively high buffering capacity, and modern farming practices which incorporate effective adaptation strategies may potentially help farmers overcome many of the adverse deposition effects (RMCC, 1990).

UV-B is also well known to suppress the growth of many crops, although research on the interaction effects with O_3 has produced somewhat varying results. In part, this is due to the fact that high O_3 levels may actually attenuate the intensity of surface UV-B, perhaps as much as 10% in industrialized regions. Nonetheless, the information on biotic interactions involving UV-B and O_3 tends to be highly fragmented, and further research is needed to fully understand the additive, synergistic, or antagonistic effects of multiple atmospheric stresses. The effects of UV-B, for instance, could be so significant that it may actually overwhelm the enhanced effect from elevated levels of CO_2, resulting in an overall reduction in crop growth (van de Staaij *et al.*, 1993).

The interactions with climate are also important. Although the overall net effect of climate change upon Canadian agriculture may be positive given the ability of farmers to adapt, there are many climatic factors that can adversely affect crop production (Brklacich *et al.*, 1997). These include changes in temperature, precipitation, sub soil moisture, available heat units, length of growing season, and the frequency, severity and duration of extreme events. How other atmospheric stressors interact under climate change conditions is not clear, although the effect of drought upon plant response to acid deposition suggests that the adverse interactive effects could be significant.

5.2 Social Welfare

There are various ways of defining social welfare, but generally it can be defined in terms of the social, cultural and economic conditions affecting individuals, families and communities. The BMA (1998) provides a useful description of the kinds of issues that shape and determine social welfare. This includes objects that have intrinsic social value; social factors which together constitute the quality of our lives; natural assets such as natural beauty, outlooks and scenic routes; historical and heritage assets; cultural and religious assets; and aesthetic assets. In the context of co-benefits, social values can be measured in terms of the degree that atmospheric conditions affect the enjoyment by Canadians of these natural, social and cultural assets. However, atmospheric assessments tend to focus upon a narrow and selective set of social welfare indicators, typically incorporating only those that can be more easily valued.

Atmospheric stresses can affect social welfare by both direct and indirect effects. Acid deposition is a good example of direct and cumulative effects, as it can harm the urban environment by damaging buildings, bridges, historical monuments and other structures. These direct effects can be potentially large, through the accelerated corrosion of metals, as well as the decay of limestone and sandstone. Although the cost of such effects has not been valued in Canada, preliminary studies in Europe estimate that the economic value of damage to buildings caused by air pollution is approximately several hundred dollars per tonne of SO_2 emitted (TAETG, 1997).

Air quality can also have an indirect effect upon social welfare, by affecting the visibility of natural and cultural assets. There are six primary particle species that affect visibility: sulphate, nitrate, elemental carbon, organic carbon, fine-particle dust, and coarse-particle dust (Austin *et al.*, 1998). Typically measured in deciview units, visibility is also perceived to be an indicator of air quality, and as such represents an important marker used by Canadians to measure their quality of life (TAETG, 1997). Establishing a value for visibility, however, is a subjective and difficult exercise as it involves both use and nonuse values. As TAETG (1997) note, how Canadians feel about being able to see mountains clearly or view a brownish haze suspended over a city's skyline is an aesthetic question that is not well measured by economists. Even the ecologically sensitive Arctic is not immune to haze, with cold temperatures and the lack of precipitation causing pollution from LRT (mainly from Russia and Europe, and to a lesser extent from North America, China and Japan) to be trapped for weeks in the atmosphere. Arctic haze has increased dramatically, 75% since 1956, and in 1989 was estimated to cover an area of between 800 - 1300 km across (Environment Canada, 1989). Although four sites across Canada are currently being monitored for visibility (Environment Canada, 1997a), there is no mention of values for the impairment or improvement of these views in the 1997 Canadian Acid Rain Assessment.

Preliminary studies in the U.S., however, provide some indication regarding both the absolute and relative values for the co-benefits of improved visibility. In their analysis of co-benefits of air pollutant emission reductions in Maryland, Austin *et al*. (1998) calculated recreational visibility (derived from a national park) to be worth $21 million, with residential visibility (based on views of Washington, D.C.) considerably less at $1.2 million. When compared to estimated human health benefits of $700 million in the same study, human health effects clearly dominate visibility effects by many orders of magnitude. On a per capita basis, benefits of $116.80, $5.60, and between $1.60 - $2.0 were calculated for human mortality, human morbidity, and visibility, respectively. Abt (1998) calculated similar relative magnitudes for human health in relation to visibility.

5.3 Human Health

In this section the implications of improvements in air quality for mortality and morbidity are presented, including projections of reduced effects from reductions in criteria pollutants that have been directly addressed in Canadian studies. While air quality has received the brunt of attention in the literature, less is known about the benefits and costs for human health from air toxics and other atmospheric pollutants.

Air quality and human health

It has long been known that the combustion of fossil fuels produces air pollutants, which are harmful to human health. Despite the fact that relatively stringent air quality standards in both Canada and the U.S. have led to improvements in air quality, research continues to demonstrate a link between ambient air quality and several adverse human health effects, even at the current concentrations. Initially, research and abatement policies targeted SO_2, but during the past decade the focus has shifted to gaseous pollutants and particulate matter. Recent studies show a relatively strong association between coarse particles (PM_{10}), fine particles ($PM_{2.5}$) and adverse human health effects (TAETG, 1997; USEPA, 1997b).

Relative to other impacts and effects, the implications of air quality upon human health have been examined extensively in the literature (Lang *et al*., 1996; Liu, 1997; and Wilby *et al*., 1997). In general, there are three major types of health studies:

1. epidemiological studies, which evaluate statistical relationships between exposures to ambient air pollution and the health effects in the human population;
2. human clinical studies, which involve exposing human subjects to limited levels of air pollution in a carefully controlled and monitored laboratory environment; and
3. toxicology studies, which directly expose human or animal tissue to air pollutants and measuring the effects.

Most studies assessing human health effects for large population groups have tended to be based on epidemiological research.

In 1985, the American Thoracic Society introduced the concept of the health pyramid to measure the effects from air pollution (Fig. 5.1). Demonstrating the cascading effects of air pollution, mortality is at the apex, with less severe and more common outcomes at progressively lower levels of the pyramid. There is strong evidence in the literature that key air pollutants such as SO_2, O_3 and PM follow a similar cascading, pyramid-like pattern of human health effects.

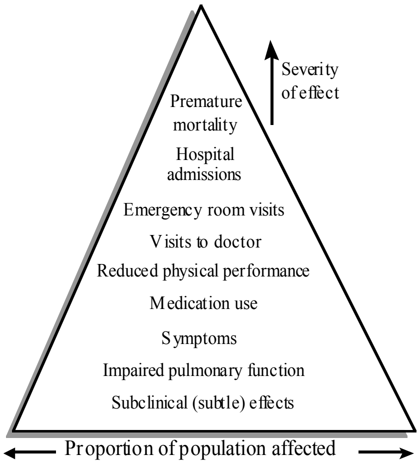

Figure 5.1 Air pollution health effects pyramid (Love *et al.,* 1998)

Providing a definitive description of health effects is a difficult task, due to many uncertainties and knowledge gaps in the literature. Nonetheless, some generally accepted relationships can be identified. According to Love *et al*. (1998), the evidence supports that:

- premature mortality is consistently associated with exposure to inhalable (PM_{10}) and respirable ($PM_{2.5}$) particulate pollution, especially sulphate; frequently with SO_2; and in some studies with NO_2 and CO;
- hospital admissions for cardiac and/or respiratory disease occur for all major pollutants emitted or produced by fossil fuel combustion;
- for O_3, fine particles (especially sulphate), and possibly SO_2, there is no evidence of a threshold of effects for the population as a whole to these pollutants; and

- it is possible to estimate quantitatively the burden of ill health on a given population based on the ambient concentration of pollutant to which they are exposed.

Secondary pollutants, which are formed when acidic emissions such as oxides of sulphur and nitrogen, and VOCs are chemically transformed into sulphates, nitrates and organic aerosols, are particularly damaging pollutants. Very small in size, they can take solid or liquid form, and are acidic in nature. Because of their small size (often less than 1 micrometre) and chemical reactivity, they can penetrate far into the lungs and injure delicate tissue. In a comprehensive study of U.S. cities, Pope *et al*. (1995) found that sulphate and fine particulate air pollution were associated with a difference in mortality risks between the most polluted cities vis-a-vis the least polluted cities of approximately 15-17%. The findings in this study also show that cumulative chronic effects can be worse than acute, short-term effects.

Recent research on the association between respiratory and cardiac diseases and air pollution in Canadian cities has demonstrated that synergistic effects may be greater than previously believed (Burnett *et al*., 1997; HEIAPR, 1997; Burnett *et al*., 1998). In these studies, it was found that the ambient air pollution mix had a greater human health affect than PM_{10} and even $PM_{2.5}$. Of the criteria pollutants, NO_2 was found to have the largest effect on mortality (with a 4.1% increased risk), followed by O_3 (1.8%), SO_2 (1.4%) and CO (0.9%). Since NO_2 is not widely considered to be a risk factor compared to other criteria pollutants in North American cities, these findings suggest that policy makers need to take a more expansive and comprehensive view of air pollutants. As Burnett *et al*. (1997) note:

> underestimates of the public health benefits of air pollution mitigation strategies, in which primary emissions of gaseous pollutants are reduced to limit secondary formation of particulate aerosols, could occur if all the benefits are attributed only to reductions in particulate mass (p. 620).

Projections of benefits

To estimate the potential benefits for human health in Canada from reductions in GHG-related emissions, a useful starting point is the comprehensive study conducted by the Working Group on Public Health and Fossil-Fuel Combustion (Lee Davis *et al*., 1997). In this study, estimates of co-benefits from GHG-related emission reductions for human health are calculated on a global scale. Expressed in terms of avoided premature mortality, the estimates are based upon a hypothetical climate policy of a 15% and 10% reduction in GHG emissions by the year 2010 for developed and developing countries respectively. PM is treated as the sentinel air pollutant, with emissions and concentrations of both coarse and fine particles considered. By the end of the second decade of the next century, just over 700,000 premature deaths would be avoided on an annual basis if the above emission reductions were achieved by this time, of which 138,000 would occur in developed countries. For the U.S., it is estimated that at least 33,000 deaths a year could be avoided by 2020, which is the same order of magnitude that currently occurs from human immuno-deficiency and chronic liver diseases.

The study does not specifically provide data for Canada. Nonetheless, one assumption might be to apply a proportional estimate based on current differences in total population. Assuming a 1:10 ratio, a crude estimate would be approximately 3,300 avoided premature deaths in Canada. However, there are many uncertainties imbedded in this estimate, and the number of avoided deaths is likely to be quite different. On the one hand, the study only addresses PM and does not take into account the full range of criteria pollutants, such as NO_2, SO_2, O_3 and CO. Neither is morbidity included in the study, and not all age groups are considered in the mortality estimates. Consequently, the estimates can be considered conservative, and the actual value of benefits will be higher. On the other hand, the projected emission reductions are somewhat higher than those agreed upon in the Kyoto Protocol; hence, one can anticipate that reductions in adverse effects will be less than projected in the study.

TABLE 5.1 Scenarios for SO_2 Reductions

Estimated benefits, all provinces, of 25%, 50% and 75% Emission Reduction Scenarios, undiscounted totals for 2010-2025

Central Estimate: 1994 C$ (000s)

Scenario	Mortality	Airway Obstructive Disease cases	Respiratory Hospital Admissions	Cardiac Hospital Admissions	Emergency Room Visits	Asthma Symptom Days	Restricted Activity Days	Acute Respiratory Symptom Days	Child Bronchitis Cases	Household Material Soiling	All Endpoints
25% Emission Reduction	12,978,965	3,292,648	13,233	13,730	5,421	60,604	130,654	602,819	55,313	139,559	17,292,856
50% Emission Reduction	35,271,136	8,944,406	35,963	37,311	14,731	164,695	354,619	1,638,250	150,544	379,260	46,990,916
75% Emission Reduction	53,210,806	13,492,637	54,254	56,289	22,223	248,463	534,974	2,471,503	227,128	572,160	70,890,436

Central Estimates: Avoided Events

Scenario	Mortality	Airway Obstructive Disease cases	Respiratory Hospital Admissions	Cardiac Hospital Admissions	Emergency Room Visits	Asthma Symptom Days	Restricted Activity Days	Acute Respiratory Symptom Days	Child Bronchitis Cases
25% Emission Reduction	3,245	11,315	2,036	1,654	9,034	1,236,819	1,764,383	430,581,759	153,646
50% Emission Reduction	8,818	30,737	5,533	4,495	24,551	3,361,132	4,792,155	117,017,835	418,178
75% Emission Reduction	13,303	46,366	8,347	6,782	37,039	5,070,677	7,229,383	176,535,894	630,911

Source: Adapted from Tables 6, 7 and 9, TAETG (1997)

TABLE 5.2 All Provinces, Benefits of a 50% Canada Only Emission Reduction Scenario, undiscounted totals for 2010-2025

	Mortality	Airway Obstructive Disease cases	Respiratory Hospital Admissions	Cardiac Hospital Admissions	Emergency Room Visits	Asthma Symptom Days	Restricted Activity Days	Acute Respiratory Symptom Days	Child Bronchitis Cases	Household Material Soiling	All Endpoints
Central Estimate: 1994 C$ (000s)	890,057	226,625	908	942	372	4,156	8,981	41,332	3,761	9,571	1,186,704
Central Estimates: Avoided Events	3,328	11,649	2,088	1,697	9,267	1,268,639	1,815,428	44,158,258	156,256	N/A	N/A

Source: Adapted from Tables 8, TAETG (1997)

Notwithstanding these and other uncertainties, evidence from the broader literature further demonstrates that benefits for human health could be significant in Canada if reductions in GHG-related emissions resulted in improvements in air quality and acid deposition. This research includes projections of avoided health effects from reduced air pollution emissions in transportation, largely through sulphur reductions in gasoline and diesel fuels (CCME, 1995; HEIAPR, 1997), acid deposition (TAETG, 1997), and NO_X/VOCs (Ontario Ministry of Environment and Energy, 1996). The benefits identified in the TAETG (1997) study are summarized in Table 5.1, and demonstrate that improvements in air quality and reductions in acid deposition could lead to significant improvements in the human health of Canadians. Similar benefits for human health have been linked to reductions in emissions from coal-fired electric power stations (Love *et al*., 1998). The latter raises the issue of transboundary pollution, and the importance of emission reductions in the U.S., in terms of benefiting the environment, social welfare and human health throughout Eastern Canada (Chestnut, 1995). The benefits of a 50% emission reduction scenario for human health could be 40 times greater with U.S. participation, relative to Canada participating alone.

While assessments of sulphur content in gasoline and diesel fuels take into account the effects from benzene, a well known carcinogen, there are few studies that examine the effects from toxic substances. This raises the question regarding the HAPS and toxic substances being emitted into the atmosphere and their adverse effects upon the environment, social welfare and human health. Numerous toxic contaminants can be directly attributed to emissions from fossil fuel combustion (Health Canada, 1998). Fossil-fired electricity generation, for example, emits a wide range of toxic substances, many of which are included in the Priority Substance List (Table 5.2).

Table 5.2 A selection of toxic substances believed to be released from the fossil fuel electric power generation sector

- inorganic arsenic,
- inorganic cadmium
- hexavalent chromium compounds
- inorganic flourides
- nickel compounds
- mercury
- polyaromatic hydrocarbons
- benzene
- dibenzodioxins/dibenzofurans
- trichloroethylene
- lead
- dichloromethane

Source: Environment Canada (1997b)

While estimates of health effects and the value of benefits has not yet been made regarding reductions in the emission of toxic substances, their inclusion would undoubtedly increase the magnitude of co-benefits. In a recent report, it was estimated that using natural gas instead of coal to generate electricity would result in considerable benefits for human health (Diener Consulting & Acres International, 1998). An 83% reduction of SO_2 emissions from power generation will also reduce other toxic air pollutants that are emitted from coal-fired electric plants by an equivalent amount. This includes arsenic, cadmium, chromium, lead and mercury, which in some cases can be nerve toxins or carcinogens. Although the overall contributions of these emissions tend to be variable as a percentage of the national totals, the potential reductions in emissions directly attributable to replacing coal-fired electric power plants are substantial.

Lastly, there are many indirect effects that could result from GHG-related emission reductions, yet they tend to be ignored in most assessments. Indirect effects could occur through groundwater, soils and the food-chain, affecting ecosystems, the environment and eventually human health. There are few, if any, examples in the literature that have comprehensively valued these effects. When they are discussed, it is usually done so qualitatively and with little indication of their relative magnitude. Acid deposition, for example, could acidify water supplies and soils, resulting in the subsequent mobilization of heavy metals, such as cadmium, mercury, lead, arsenic and aluminum (Liu, 1997). As a result, increased human exposure to these metals would occur through water supplies and the food chain. What is less clear is the monetary value of reducing the exposure risk to these pollutants.

5.4 Exterrnalities

The vast majority of research on effects has focused on those that could be attributed more directly to emissions, yet many anthropogenic activities that involve reductions in the combustion of fossil fuels can also generate additional impacts and effects on the natural and human environment. These "externalities" refer to the impacts that affect those that not targeted by a specific project or policy. In the broader literature on impact assessment, emissions of air pollutants and the resulting impacts and effects upon environmental and human health are treated as just one (albeit a major one) of many externalities associated with anthropogenic activities such as transportation and electricity generation. Using the environmental impacts of roads as an example, Bein (1997) suggests that roads can contribute to air pollution, cause noise and vibrations, affect land use, consume resources, create waste disposal problems, contribute to water pollution, affect hydrology, form barriers to people, wildlife and agriculture, and diminish biodiversity.

As such, co-benefits are a subset of externalities, although in our assessment framework externalities refer to the impacts and effects that are not directly related to emissions, air quality or other atmospheric issues. Depending upon the anthropogenic activity, actions to reduce GHG-related emissions can generate a wide range of benefits and costs that are not directly attributed to reductions in air pollutants. For example, transportation has enormous unintentional costs, the most obvious demonstrated by the number of traffic fatalities and accidents that occur in Canada each year. Even alternatives to fossil fuel combustion, such as the generation of electricity by hydro and nuclear facilities, have non-emission related impacts and effects upon the natural and human environment.

Not surprisingly, estimating monetary values for these impacts and effects is a difficult task, and even when they are attempted in the literature, many uncertainties exist. Studies vary in the extent of the "life-cycle" that they consider, while local impacts are often a function of site specific situations and available technology. As demonstrated in the discussion on effects directly related to emission reductions, environmental risk to externalities may also be influenced by the duration of exposure (short, medium or long term), and the spatial extent of the effects (local, regional or global). Nonetheless, the inclusion of these additional "external" impacts and effects into an assessment of co-benefits is important, since the costs and benefits associated with them often equal, and in some cases exceed, those attributed directly to emissions. Of course not all of these costs would be reduced through actions that reduce GHG-related emissions; however, depending upon the action themselves, and local circumstances, the impacts and effects could be significant. The brief case studies which follow on electricity, transportation and residential energy efficiency illustrate the complexity of measuring non-emission related effects, the opportunities that they represent, and their potential relative importance to the overall estimates of co-benefits.

Electricity:

Electricity is essentially clean at the end point use, but as was noted above its generation via the combustion of fossil fuels entails some adverse impacts and effects. Not all of the effects, however, are restricted solely to emissions at the point of generation. If the life-cycle of energy is considered, then a full accounting of effects would include all potential impacts that occur at each stage of the energy system and fuel cycle, which could be substantial and varies considerably within and between energy groups (Ottinger *et al.*, 1991; International Expert Group 3, 1991). The life-cycle sequence considers the risk of fatalities, diseases and injury to workers (occupational health) and the public, from activities involved in the fuel extraction (mining, drilling and harvesting), construction, transportation, treatment, storage, utilization or conversion (including waste management), and decommissioning of energy generation facilities. Even hydroelectric power will generate impacts and effects upon environmental and human health. Relative to electricity generation from fossil fuel combustion, hydroelectricity has the advantage of not producing air pollutants or GHGs apart from that created during material preparation and facility construction. As Ottinger *et al*. (1991) point out, environmental impacts result from (i) changes in river flow characteristics; (ii) changes in the ecosystems of land flooded to form reservoirs; and (iii) erection of barriers which interfere with the natural movements of fish and wildlife.

Although a comparative risk assessment of different energy systems must be treated with extreme caution, some general trends are demonstrated in the literature. The fossil fuel group (coal, oil and natural gas) has relatively high accident rates that dominate occupational risks, and the burning of fossil fuels produces relatively large amounts of gaseous and solid wastes that dominate public health risks. The renewable group (wind, solar and thermal) is characterized by low public risk and relatively high occupational risk from the construction phase. In contrast, the nuclear group exhibits occupational risks that are dominated by mining and power production related accidents. Public risk is relatively low during normal operations, but long term waste management and the potential for severe accidents add considerable risk and uncertainty to this energy option. The cost of reducing health risks during the final decommissioning stage has been estimated to range from 5-100% of the total costs of the nuclear life-cycle (Ottinger *et al*., 1991).

Due to the complexity of the task, there have been few attempts to assign values to the effects from each stage of the life-cycle. Krewitt *et al*. (1998) attempt to do so in terms of human health effects, and demonstrate that solid and liquid fossil fuels have the highest loss of life expectancy. Combined cycle natural gas has the lowest risk amongst fossil fuels, and its effects are even lower than those attributed to the photovoltaics fuel chain, as the latter generates adverse effects during the material supply and component production stage. Nonetheless, it is becoming more widely accepted that a combination of natural gas, renewable and actions that involve energy conservation and efficiency are the most environmentally safe options currently available.

Transportation

Transportation has been clearly identified as a major contributor to air pollution, but unintended consequences of transportation are also enormous. Traffic fatalities and injuries from accidents quickly come to mind, but externality effects can also be extended to include unwanted noise, its role as a significant consumer and shaper of land use, traffic congestion, and resource consumption (Greene *et al*., 1997). Each of these have concomitant effects upon the environment, social welfare and human health.

Although challenging and difficult to estimate, some attempts at valuation can be found in the literature (BMA, 1998; Greene *et al*., 1997; Quinet, 1997; Lakshmanan *et al*., 1997; Bein, 1997; Osborne Group *et al*., 1995). Quoting a European Commission study, Lakshmanan *et al*. (1997) estimate that the aggregate external costs of land transport can reach levels up to 5% of GDP, with the following distribution: air pollution (excluding global warming), 0.4%; noise, 0.2%; accidents, 1.5%; and congestion, 2.0%. Similarly, the BMA (1998) estimated that for the U.K., the environmental costs of transportation could be allocated accordingly: air pollution, 1.12% (urban), 0.52% (other); air pollution (health effects), 1.5%; noise, 1.0%; and water pollution, 1.2% of GDP.

While significant modal shifts in transportation from single occupant vehicles into public transit, or truck transport to rail freight will result in avoided costs less that those estimated above, a significant degree of co-benefits can be expected, depending upon the actions taken. However, none of the research to date has attempted to value the percentage of avoided damages that may occur from moderate reductions in GHG-related emission reductions in the transportation sector. Assessments of modal shifts in transportation should also take into account the benefits of promoting healthier forms of transport, such as walking and cycling, which has been widely documented as improving individual and public health. Although walking and cycling have their own inherent risks, increased physical activity has been shown to reduce the risk of coronary heart disease and stroke, obesity and hypertension, and be an effective treatment for depression and anxiety (BMA, 1998).

Residential energy efficiency:

Improving energy efficiency in the residential sector is a useful example of indirect benefits and costs. It also demonstrates that actions to reduce GHG-related emissions can be relatively affordable, distributed widely, and generate external benefits that could exceed those attributed solely to reduced emissions (and resulting improvements in outdoor air quality). In response to the energy crisis of the 1970s, the energy efficiency of residential homes and commercial buildings have improved significantly throughout that decade and the 1980s. However, by adding insulation and taking other steps to reduce heat loss, these actions also reduced ventilation, thereby increasing or prolonging occupant exposure to various indoor contaminants (Ottinger *et al*., 1991). During the 1990s improved technology and better choices in materials has allowed for the construction of energy efficient buildings that also provide a healthier indoor environment. However, new buildings continue to be constructed that do not follow building standards for indoor environments, and the problem continues to persist in many residential and commercial buildings.

There is growing evidence which demonstrates that indoor air quality in buildings constructed throughout the 1970s and 1980s represents a major proportion of the public's exposure to air pollution, and that it may pose a serious acute and chronic health risk. On average, Canadians spend between 75-90% of their time indoors (Hancock *et al*., 1998), and that in such environments they are exposed to a variety of pollutants. These include NO_X from gas appliances or malfunctioning oil furnaces, toxic compounds from building materials and furnishings, VOCs from photocopiers and carpets, in addition to biological contaminants (Ottinger *et al*., 1991; Roberts, 1998). Children are particularly at risk to indoor environments (Hancock *et al*., 1998). Indoor air quality and energy efficiency can be compatible goals, and actions which accomplish both through improved building standards, may also have the added co-benefit of increasing the resilience of homes and buildings to impacts of climate change (e.g. extreme events).

5.5 Conclusions

There is little doubt that a wide variety of effects will occur from reductions in GHG-related emissions. While most of the benefits that result from these effects have been attributed to human health in studies of co-benefits, through improved air quality, and especially reduced exposure to PM, there is strong evidence to suggest that significant benefits may be experienced elsewhere. This includes benefits from avoided damages to forestry, agriculture and social welfare, while for human health the benefits include avoided premature deaths and illnesses that are not directly caused by reductions in PM. If non-emission related external effects from the actions to reduce GHG-related are also included in the assessment, then the overall value of benefits is likely to be greater by many orders of magnitude than previously estimated.

Due to many uncertainties and knowledge gaps throughout the literature, however, the potential magnitude of benefits remains uncertain. While the literature clearly demonstrates that impacts and effects will occur, there is insufficient information to evaluate them in terms of their monetary value. The lion's share of benefits will continue to be in the area of human heath, but the relative magnitude of other effects will be greater than estimated in previous studies.

6.0 THE SIGNIFICANCE OF SCALE

The connection between global scale problems and local actions has received considerable attention in the literature, especially from a climate change perspective. This includes the importance of regional scale analysis in assessing climate change impacts, in addition to developing appropriate mitigative actions to reduce GHG emissions. The connectivity between global, national and regional scales is also inherent to the co-benefits issue from a variety of perspectives. Many of these have been mentioned extensively throughout this paper, reflecting the importance that regional scale analysis has been granted in much of the co-benefits literature. Further, the importance of regional scale analysis may be particularly pertinent to the Canadian situation.

The selection of scale is best determined by the specific parameters of the research problem. In some cases, a global or continental scale is necessary, especially for large scale issues where multinational or bi-national policy agreements are necessary. Even in this case, however, knowledge at the national and regional scale may be needed, to help shape and determine a Canadian position in the international arena. The climate change impacts issues, for example, is inherently regional in Canada, and the policy debate demands an informed knowledge base at the regional scale (Chiotti, 1998).

A similar, if not stronger, argument can be made for the issue of assessing the impacts and effects from GHG-related emission reductions. First and foremost is the inherent connection between global and regional scales, in terms of atmospheric processes and the spatial level at which the co-benefits from GHG-related emission reductions are likely to be experienced. In chapter 4, it was demonstrated that atmospheric issues operate at various spatial and temporal scales, but those specific to air pollution are largely regional in character. While some atmospheric issues such as climate change and variability, and stratospheric ozone depletion, are global in nature, their interaction with other atmospheric issues are also regional in scope. The global scale issues generate effects that will be felt over many decades, if not centuries, and actions to reduce emissions which cause these issues will take many years before noticeable improvements occur.

Other atmospheric issues, such as acid deposition, O_3, PM, and HAPS/toxic substances, tend to be more regional in nature. In particular, local meteorology and geography can affect the temporal and regional distribution of emissions and ambient pollutant concentrations. Reducing emissions that contribute to these air pollutants can also generate immediate and localized benefits. In addition, reductions in pollutants, which contribute to regional scale atmospheric issues, will have similar scale benefits in terms of their interactions with the impacts and effects from climate change and stratospheric ozone depletion. As TAETG (1997) notes, in terms of SO_2 emissions and the effects from acid deposition, “the benefits of reducing emissions are greater in areas close to the polluter than in areas some distance away” (p. 20). This is also the case with the precursors to O_3, such as NO_X, VOCs and PM.

Second, in Canada sources of air pollutant emissions and deposition patterns are highly regional. Data from the National Pollutant Release Inventory clearly establish regional variations and concentrations in emissions for various pollutants, notably PM, SO_X, NO_X, and VOCs. With the exception of the energy sector in Alberta and some sectors of the economy (e.g. pulp and paper, non-ferrous mining and smelting industry), a majority of emissions are generated in specific regions, whereas others tend to be indigenous to urban areas. The chief sources of air pollutants include transportation, electricity generation and industrial activity, which are spatially variable across Canada. Since the magnitude of impacts and effects are closely dependent upon the actions chosen to reduce emissions, it follows that actions also need to be assessed at the regional scale.

Emissions from electricity generation, for example, are directly related to the fuel type and energy mix, and in Canada the regional pattern of production is quite distinct (Table 6.1). In 1996, coal-fired plants were prominent generators of electricity and by extension major sources of air pollutants in Alberta, Saskatchewan, Ontario, Nova Scotia and New Brunswick. This differs quite noticeably from the relative importance of hydro in Quebec, Manitoba and British Columbia, as well as nuclear energy in Ontario. In the latter case, the premature retirement of nuclear plants and the replacement by coal and oil fired plants could add to Ontario's position as Canada's largest emitter of air pollutants.

Third, the very nature of co-benefits implies a close relationship between emissions and concentrations of atmospheric pollutants, in association with the receptor community. In the latter case, this involves either impacts upon aquatic and terrestrial ecosystems, or effects upon the environment, social welfare and human health. In chapters 4 and 5 it was demonstrated that impacts and effects of acid deposition and air quality are regional in character, being especially prominent in Eastern Canada and major urban centres. This is perhaps most apparent for human health and the location of vulnerable groups, but it also applies to the forestry and agriculture sectors that are particularly sensitive to air pollution or where concentrations of pollutants are especially high.

Fourth, the issue of transboundary pollution is a major problem in some regions of the country, but not in others. This involves upwind pollution from the U.S., in addition to downwind pollution from one part of Canada to another. Southern Ontario, parts of Quebec and the Maritime Provinces are particularly impacted by transboundary pollution, specifically in terms of acid deposition and O_3. The Ohio Valley and coal-fired electricity plants are well known polluters, which have been estimated to generate up to 50% of southern Ontario's air pollution (Ontario Ministry of Environment and Energy, 1996). Furthermore, scenarios of emission reductions in the U.S. have been shown to generate significant benefits for human health in Ontario and eastern Canada (Love *et al.*, 1998; Chestnut, 1995). As TAETG (1997) clearly demon-

Table 6.1 Electricity Energy Generation (GWh) by Fuel Type - 1996

	Coal	Oil	Natural Gas	Nuclear	Hydro	Other	Total
Nfld.	0	1,480	0	0	35,336	0	36,816
P.E.I.	0	6	0	0	0	0	6
N.S.	7,850	788	0	0	1,151	187	9,976
N.B.	5,474	1,246	0	4,591	3,472	571	15,354
Quèbec	0	1,368	0	5,232	163,861	0	170,461
Ontario	18,899	141	5,078	77,693	40,945	891	143,647
Manitoba	180	35	32	0	30,865	60	31,172
Sask.	11,225	10	769	0	4,386	122	16,512
Alberta	41,518	70	6,727	0	2,261	1,200	51,776
B.C.	0	145	3,315	0	66,300	964	70,724
Yukon	0	139	0	0	361	0	500
N.W.T.	0	475	102	0	260	0	837
Canada	**85,146**	**5,903**	**16,023**	**87,516**	**349,198**	**3,995**	**547,781**

Source: Electric power annual statistics - 1996, Statistics Canada, catalogue 57-202 (June 1998); Electric power statistics - September 1998, Statistic Canada, catalogue 57-001 (December 1998); Quarterly report on energy supply-demand in Canada - 1997 - IV, Statistics Canada, catalogue 57-003.

strates, whatever benefits are experienced in the regions of southern Ontario and eastern Canada will be influenced by actions taken south of the border.

Fifth, other air pollution reduction policies are predominantly regional in nature. While the transboundary nature of acid deposition and air quality requires the added dimension of bi-national cooperation, most of the policy decisions are of a regionally specific nature. This may be particularly the case for air pollution where various municipal and provincial policies are in place that are directed at reducing emissions. This places great importance in situating GHG-related emission reductions within the context of regional conditions, especially for reasons of harmonization. As Olivotto (1997) notes, each O_3 problem area will require the design of different emission reduction strategies. This is due to geographical and meteorological factors, in addition to the spatial and temporal dimensions of emission sources. In the case of sulphur reduction in fuels, for example, the Lower Fraser Valley already has aggressive policies in place that regulate sulphur content in diesel fuels. Hence, the benefits of sulphur reductions may be greater in major urban areas with less stringent controls, such as Toronto and Montreal relative to Vancouver (CCME, 1995).

Sixth, the disconnection between national, provincial and regional scales becomes more problematic in the context of assessing appropriate GHG-related emission reduction strategies. MacIver et. al. (1999) demonstrate that the data for different atmospheric issues and information on ecosystem impacts and environmental effects tends to be disconnected in terms of spatial scale. Too often atmospheric concentrations and resulting impacts and effects are extrapolated or downscaled at the regional scale, from national or provincial scale data. Inevitably, this results in a loss of differences in values within and between regions, through the aggregation process. Provincial and national aggregation tends to present a more homogeneous portrait of emissions, atmospheric concentrations, impacts, effects, etc., glossing over the richer heterogeneity and interactions that regional scale analysis provides. The regional scale may be the level of analysis where the synergistic, antagonistic and non-linear relationships can best be assessed. This is particularly the case for rural areas in southern Ontario, where the site specific measurements for air quality suggests quite a different pattern between rural and urban air quality from those typically presented at the provincial scale (Chiotti and Bain, 1999). By extension, such subtle differences in air quality could have profound implications for ecosystems, the environment and human health, which would otherwise be lost in analyses at the provincial scale.

In conclusion, there is little doubt that an assessment of the impacts and effects from GHG-related emission reductions would greatly benefit from regional scale analyses. There are other reasons, not mentioned here, that also substantiates the value of regional scale analyses. One in particular is worth noting. It can be expected that local actions to reduce GHG emissions will be very important to the national effort to meet the targets set out in the Kyoto Protocol. Demonstrating the value of co-benefits at the municipal, community, neighbourhood and individual (firm and household) levels of analysis would considerably improve “Buy-on” at the regional scale. Addressing co-benefits represents an opportunity to bring what is widely perceived by the general public to be a global scale and future phenomenon into the backyards of Canadians today, rather than tomorrow. As suggested throughout the literature and in this paper, GHG-related emissions reductions should be applied in regions where the greatest benefits are to be felt. Regional scale analysis will greatly facilitate the generation of this information.

7.0 NEXT STEPS: PHASE II ACTION PLAN

The purpose and objectives of this overview paper have been to provide a preliminary qualitative assessment of the relative magnitude of the impacts and effects from actions and measures that reduce GHG-related emissions. It is evident from this assessment that the issue of co-benefits is vast, complex and involves many interactions, uncertainties and knowledge gaps. While our understanding and estimates of impacts and effects can be made with confidence in some areas, in others much uncertainty remains. In part, this is due to the current state of knowledge, the science and research challenges inherent to this atmospheric problem, and our ability to value impacts and effects.

Net co-benefits are likely to be greatest in the area of human health, although the relative magnitude of other effects such as ecosystems and the environment may be greater than previously estimated. In the case of human health, the extension of the assessment framework to include gaseous pollutants and toxic substances to PM would add considerably to the value of benefits. Although the valuation of ecosystem impacts and effects upon the environment and social welfare are not well documented in the literature, from a qualitative perspective it can be expected that avoided impacts in these areas could also be substantial. With the addition of effects from non-emission related externalities associated with the actions themselves to reduce GHG-related emissions, overall co-benefits will be larger than previously estimated, potentially by an order of magnitude. Further research is needed, however, to test this assessment.

Many knowledge gaps and uncertainties have been cited throughout the paper, and could be addressed in subsequent research. These include uncertainties in:

- the impacts that emissions of air pollutants will have on the functioning of the atmosphere vis-a-vis interactions with other atmospheric issues (including climate change and UV-B);
- the actual and projected trends in emissions of air pollutants;
- the interactions between atmospheric issues and their synergistic, antagonistic and cumulative impacts upon terrestrial and aquatic ecosystems;
- the interactions between atmospheric issues and their synergistic, antagonistic and cumulative effects upon forestry and agriculture;
- the effects and valuation of social welfare benefits from reduced air pollution;
- the interactive effects upon human health;
- non-emission related externalities that occur from the actions to reduce GHG-related emissions and their effects upon environmental, social welfare and human health;
- the complimentarity of actions to reduce GHG-related emissions with policies which address specific atmospheric issues or pollutants; and
- the level of knowledge regarding impacts and effects at the regional scale.

Given these uncertainties and knowledge gaps, it is possible that even the most sophisticated quantitative models will be unable to produce with complete confidence comprehensive estimates of co-benefits. Broadening the impacts assessment and valuation introduces considerable uncertainty into the assessment process, especially in terms of non-market and less tangible goods. With this scoping paper, we now have a better sense of the relative magnitude of impacts and effects, but we need to have a clearer understanding of their importance at the national and regional scale. A qualitative approach to assessing impacts and effects from reductions in GHG-related emissions may be the most practical and productive method to overcome these uncertainties and knowledge gaps.

This overview scoping paper represents the first step in the process to improve our knowledge of the relative magnitude in impacts and effects of GHG-related emission reductions in Canada from a qualitative perspective. Together with the background report Atmospheric Change in Canada: An Integrated Overview, the papers serve as a foundation from which to launch further steps as a Phase II Action Plan. The two background papers are also useful as a science assessment, to help the National Issues Tables assess the impacts and effects in the development of their proposed actions. The writing of these papers has also resulted in the development of considerable knowledge and expertise regarding the issue of co-benefits. In conjunction with the establishment of an advisory board and scientific panel to provide expert judgment, this knowledge could also be made available to the National Issues Tables during the “roll-up” phase through a more comprehensive assessment of their proposed actions.

Given the connectivity between global, national and regional scales cited in chapter 6, it is recommended that an integrated-qualitative approach that draws upon expert judgment to assess co-benefits should be adopted in further work at both a national and regional scale. Such an approach may be the most practical and productive method to overcome the many uncertainties and knowledge gaps cited in this paper. The key question becomes less directed at whether or not a regional scale assessment is needed, but rather which region in Canada is best suited for such an assessment? First, the region should exhibit most if not all of the regional attributes described in chapter 6, so that it can best compliment a national scale assessment. Second, detailed information will be needed, for criteria air pollutants (emissions and ambient air quality) including toxic substances, aquatic and terrestrial ecosystems, the environment (agriculture or forestry), social welfare and human health. Due to time and resource constraints it will be necessary to act swiftly and effectively to produce announceables for the Joint Ministers of the Environment meeting scheduled for December. A strong research team will be needed that can assemble the appropriate scientific expertise to qualitatively assess the impacts and effects of the options proposed by the Issues Tables to reduce GHG emissions. Third, the region selected should be large enough that actions to reduce GHG-related emissions will generate meaningful quantities of benefits at the regional and national scale. However, at the same time the region selected should be able to produce lessons that can applied elsewhere across Canada.

The Toronto-Niagara Region is proposed for such a case study. The region fits most, if not all of the criteria discussed in chapter 6, in addition to those cited above. Moreover, it is a region that has been extensively examined in terms of air pollution and human health. Although subject to considerable debate, the Ontario Medical Association has estimated that 1,800 annual premature deaths in Ontario can be attributed to PM (MacPhail *et al*., 1998). Similarly, with 16,000 premature deaths due to air pollution in Canada, a large proportion is estimated to occur in southern Ontario (Government of Canada, 1998). Rising concern in the region towards air quality has spawned many policy responses at the Provincial level (e.g. the recently introduced Drive Clean program), as well as assessments at the municipal level (Pengelly *et al*., 1997). An opportunity exists to capitalize on the synergy in research and policy developing in the region towards improving air quality, by linking these initiatives with actions to reduce GHG-related emissions.

The region is also subject of a multi-stakeholder study led by Environment Canada on atmospheric change (see Mills and Craig, 1999). This assessment of both emissions and impacts (and effects) from integrated atmospheric issues has evolved beyond the developmental stage (Ogilvie *et a*l., 1997), and is currently two years into its five year work plan. Considerable expertise has been brought together in this study, including scientists from various departments of Environment Canada, partnerships with Provincial and Municipal Governments, and in collaborative relationships with many University faculty and graduate students.

Numerous work plans are already supported in this initiative, including research on ecosystems and biodiversity, the development of urban and ecosystem assessment frameworks, integrated mapping of ecosystems and atmospheric issues, human health, and energy. In the latter case, PERD project number 24114 has received funding to undertake research on climate change and energy in the Toronto-Niagara Region, involving stakeholder participation. This project specifically addresses impacts and emission issues for the energy sector, and as such directly compliments the co-benefits work being proposed for Phase II (Auld *et al*., 1999).

The TNR study also has a strong working relationship with Pollution Probe, which is nationally recognized as an Environmental Non-Government Organization. They bring considerable expertise to issues related to co-benefits, with a proven track record in the area of climate change (Ogilvie *et al*., 1997), transportation (Roberts, 1998), emissions from coal-fired electric plants (Love *et al*., 1998), and child health and air quality (Hancock, 1998). They also have representation on 6 of the Issues Tables, and co-chair the Transportation Issue Table. Further, Pollution Probe brings enormous visibility and credibility to the issue, in terms of its public recognition as an ENGO. This mya be particularly important in helping to disseminate the results of Phase II, and maximize “buy-on” from individuals, firms, agencies and communities, from both within the region and across the country.

The Phase II Action Plan proposes to undertake a qualtative assessment of impacts and effects of GHG-related emission reductions at the national scale, in addition to a regional scale analysis using the Toronto-Niagara Region as the case study. The assessment will draw upon a team of science experts with knowledge on the national and regional scale, in order to assess qualitatively the impacts and effects that may result from the actions proposed by the Issues Tables to reduce GHG emissions. This assessment will be developed along the following five pathways:

- Focus on estimating impacts and effects on ecosystems, environment, social welfare, human health and the actions themselves to reduce GHG-related emissions, and assigning relative values to these benefits.

- Estimate the full suite of co-benefits from the most likely actions that may be adopted in the national implementation strategy.

- Assess the GHG options proposed by the respective Issues Tables in terms of co-benefits, and prepare a qualitative analysis.

- Simultaneously undertake this assessment at an urban-centred regional scale, where the methodology can be further refined and important lessons learned.

- Situate this regional assessment within a national context and identify other regions in Canada where similar assessments should be implemented.

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Glossary

AMG – Analysis and Modelling Group.

AQVM – Air Quality Valuation Model.

B(a)P – benzo(a)pyrene, a toxic compound.

Base cations – positive charged ions as hydrogen, calcium, ammonium.

Bioaccumulation – the process by which chemical substances are ingested and retained by organisms, either from the environment directly or through consumption of food containing the chemicals.

Biota – collectively, the living organisms in a given ecosystem, including bacteria and other microorganisms, plants and animals.

1,3-butadiene – C_4H_6, a carcinogenic compound.

CC – Chlorocarbons.

CFCs – Chlorofluorocarbons, a family of manufactured gases composed of chlorine, fluorine, and carbon, which, along with halons, are the main cause of stratospheric ozone depletion.

CO – carbon monoxide, a colourless, odourless, and tasteless gas released primarily by incomplete combustion of fossil fuels (especially by automobiles). At low doses, CO impairs reflexes and perception; at high concentrations, it can cause unconsciousness and death.

CO_2 – carbon dioxide, a greenhouse gas that is released to the atmosphere by both natural and human activities.

CH_4 – methane, a greenhouse gas emitted to the atmosphere from ecological sources such as wetlands, manure deposits, rice paddies, municipal dumps, coal mines, leaks from gas wells, and pipelines.

CGCP – The Canadian Global Change Program founded in 1985 under the auspices of the Royal Society of Canada, coordinates research and community results, ideas, and recommendations to the policy community.

Catalyze – performing change in the rate of chemical reaction brought about by small amounts of a substance that is unchanged chemically at the end of the reaction.

Co-benefits – potential effects of reducing GHG which translate in net benefits in other areas.

Chloroplast – a plastid containing chlorophyll, the building block of photosynthesis and starch formation.

Chlorosis – yellowing and blanching of the normally green parts due to causes other than absence of light.

Critical load – the highest level of deposition below which significant harmful effects do not occur.

Chromium – a hard white metallic element that occurs as chromo-iron ore and is toxic to plants and animals.

DNA – (deoxyribonucleic acid), the genetic material of organisms and many viruses.

DDT – dichlorodiphenyltrichloroethane, a synthetic insecticide that is persistent and tends to accumulate. It is known to induce cancer. It has been banned since 1974, and last stocks were allowed to be sold until December 1990.

DOC – dissolved organic carbon.

EFM – Emissions Forecasting Model.

EIA – Environmental Impact Assessment.

Externalities – The impacts and effects that are not a consequence of reductions in emissions or improvements in air quality per se, but occur as a result of the actions such as the health benefits that accrue from a modal shift in transportation.

GHG – Greenhouse gases such as carbon dioxide, methane, ozone, nitrous oxide, and halocarbons. These gases have the strong capability to absorb long wave energy in the atmosphere and reradiate it.

HIA – Health Impact Assessment.

HCB – hexachlorobenzene $C_6CH_6Cl_6$; a systemic (meaning that it affects a whole bodily system, as the nervous system) insecticide poisonous to flies, cockroaches, aphids, and boll weevils. Also known as benzene hexachloride.

H_2O_2 – peroxy radical.

Heavy metals – A metallic element with a relatively high atomic weight (>5.0 specific gravity), i.e. cadmium, lead, mercury.

IPCC – The Intergovernmental Panel on Climate Change, a global climate change study group organized jointly by the World Meteorological Organization and the United Nations Environmental Program in 1988 to bring together leading scientists from 30 countries.

Ktonnes – 1000 tonnes.

LCA – Life-cycle Assessment.

LRT – Long Range Transport.

Mercury (Hg) – a silvery-white heavy liquid metallic element occurring naturally in cinnabar and used in barometers, thermometers and amalgams; toxic to aquatic plants and animals; accumulates in sediment and food chains.

Methyl mercury – CH_3Hg alkyl radical derived from methane that combines with mercury.

N_2O – nitrous oxide, a greenhouse gas whose principal source is agricultural soil in a degraded state.

NO_X – nitrogen oxides, a group of gases released by fossil fuel combustion, forest fires, lightning, and decaying vegetation. NO_2 nitrogen dioxide, a reddish brown gas with an irritating odour, is one of the key ingredients in smog.

NAICC – National Air Issues Coordinating Committee.

NMHC – Non-methane hydrocarbons.

nm – nanomoles, a chemical unit.

O_3 – ozone, a pungent, faintly bluish gas, which in the lower atmosphere occurs as a pollution product formed by combining nitrogen oxides and volatile organic compounds in the presence of sunlight. It is also a greenhouse gas. Above 20 km, it is produced naturally and serves to protect the biosphere from damaging ultraviolet radiation.

OB – organo bromine.

OH – hydroxyl radical.

Oligotrophic – the low state of nutrients in a water body determined by the average concentration of total phosphorus and algae growth (productivity) that the phosphorus can sustain.

PM – particulate matter.

PM_{10} – particles smaller than 10 micrometers.

$PM_{2.5}$ – particles smaller than 2.5 micrometers.

PAH – polycyclic aromatic hydrocarbons, the oldest known carcinogenic in humans, emitted from burning fossil fuels. Sources include thermal power plants, coke ovens, sewage, wood smoke and used lubricating oils.

POPs – Persistent Organic Pollutants.

ppb – parts per billion.

ppm – parts per million.

ppmv – parts per million per volume.

Phytoplankton – microscopic aquatic vegetative life; plant portion of the plankton; the plant communities that float free in the water and contains many species of algae and diatoms.

Radiative forcing – the balance of net fluxes of solar and thermal infrared radiation in the troposphere that were disturbed by gases resulting from industrial processes.

SO_2 – sulphur dioxide, a colourless gas with a pungent odour, irritates the upper respiratory tract in humans and leads to acid deposition/acid rain.

SOx – oxides of sulphur, a group of gases released by the combustion of fossil fuels and by natural sources such as volcanoes.

SIA – Social Impact Assessment.

SEA - Strategic Environmental Assessment.

Senescence – the phase of plant growth that extends from full maturity to actual death and is characterized by an accumulation of metabolic products, increase in respiratory rate, and a loss in dry weight especially of leaves and fruits.

Stratosphere – It is the layer of the atmosphere between 10 and 50 km above the Earth's surface within which temperatures rise with increasing altitude. Contains stratospheric ozone, which absorbs potentially harmful ultraviolet radiation.

Stomatal resistance – the action, through the minute openings in the epidermis, against gaseous interchange between the atmosphere and the intercellular spaces within the leaf.

Synergistic interaction – an interaction that has more than additive effects, such as the joint toxicity of two compounds being greater than their combined independent toxicities.

TSP – total suspended particles.

Thermocline – a layer of water in a thermally stratified lake or other body of water separating an upper warmer lighter oxygen-rich zone from a lower colder heavier oxygen-poor zone; especially a stratum in which temperature declines at least one degree centigrade with each meter increase in depth.

Toxaphene – $C_6H_{10}C_{18}$; toxic organochlorine compound used as an insecticide.

Toxic pollutants – Chlorinated dioxins and furans, acetaldehyde, formaldehyde, PAH, heavy metals.

Troposphere – the lowest layer of the atmosphere, extending from ground level to about 11 km above the Earth. Contains about 95% of the Earth's air and ends at the tropopause, the point at which the temperature starts to increase instead of decrease as one moves farther from the Earth.

UNFCCC – United Nations Framework Convention on Climate Change.

USEPA – United States Environmental Protection Agency.

Uni-bifacial necrosis – one or both sides of a plant leaf where death tissue is caused by an external factor such as ozone and characterized by a brownish or black discoloration.

UV-B – wavelength > 290 and <= 315 nm.

VOCs – volatile organic compounds, any organic gas such as propane and benzene, found in the vapour of substances such as gasoline, numerous solvents, and oil base paints.

WTP – willingness-to-pay.

WTC – willingness-to-accept compensation.

Zooplankton – microscopic animal life, that move passively in aquatic ecosystems.

μmg/m^3 – micro gram per cubic meter.

μg.g^{-1} – micrograms per gram.