The avoidable health effects of air pollution in three Latin American cities: Santiago, São Paulo, and Mexico City

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Abstract

Urban centers in Latin American often face high levels of air pollution as a result of economic and industrial growth. Decisions with regard to industry, transportation, and development will affect air pollution and health both in the short term and in the far future through climate change. We investigated the pollution health consequences of modest changes in fossil fuel use for three case study cities in Latin American: Mexico City, Mexico; Santiago, Chile; and São Paulo, Brazil. Annual levels of ozone and particulate matter were estimated from 2000 to 2020 for two emissions scenarios: (1) business-as-usual based on current emissions patterns and regulatory trends and (2) a control policy aimed at lowering air pollution emissions. The resulting air pollution levels were linked to health endpoints through concentration–response functions derived from epidemiological studies, using local studies where available. Results indicate that the air pollution control policy would have vast health benefits for each of the three cities, averting numerous adverse health outcomes including over 156,000 deaths, 4 million asthma attacks, 300,000 children’s medical visits, and almost 48,000 cases of chronic bronchitis in the three cities over the 20-year period. The economic value of the avoided health impacts is roughly $21 to $165 billion (US). Sensitivity analysis shows that the control policy yields significant health and economic benefits even with relaxed assumptions with regard to population growth, pollutant concentrations for the control policy, concentration–response functions, and economic value of health outcomes. This research demonstrates the health and economic burden from air pollution in Latin American urban centers and the magnitude of health benefits from control policies.

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1. Introduction

Developing regions often face critical air pollution problems due to the rapid growth of transportation and industry sources and the large number of people exposed. Three of the world’s four largest cities can be found in the rapidly developing world, where many are plagued by severe air pollution (Davis and Saldiva, 1999; Molina and Molina, 2004). Further, some populations in these areas often lack adequate access to basic health care and sound nutrition and are especially vulnerable to environmental contamination. Current levels of air pollutants have been associated with health events from mortality to chronic respiratory and cardiac problems and low birth weight (Holgate et al., 1999). Over 100 million people in Latin America and the Caribbean live in areas with air pollution concentrations above the health-based World Health Organization (WHO) guidelines (WHO, 2000).

Latin America is increasingly urbanized and faces related air quality problems, such as those associated with growth in transportation networks. About three quarters of
persons in Latin American and the Caribbean live in urban areas, and many large cities, such as Mexico City and São Paulo, have increasing levels of air pollution (UNEP, 2002). The main ambient pollutants of concern include carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO2), tropospheric ozone (O3), and particulate matter (PM). The transportation sector is estimated to account for over 40% of PM10 (PM with an aerodynamic diameter less than 10 µm) emissions in Mexico City, 86% of PM10 emissions in Santiago, and over 75% of NOx emissions for both cities (O’Ryan and Larraquibel, 2000). Pollution from the expanding transportation network is exacerbated by the older transportation fleet, low turnover of vehicles at about 10–20 years, inadequate vehicle maintenance, and traffic congestion. Other key emission sources include industry and dust from roads. Many cities in this region also have topographic and meteorological conditions that can prevent emitted pollution from dispersing, allowing the buildup of pollutants.

The aim of this study is to investigate the direct ties between various energy policies and air pollution concentrations by comparing two “what if” air pollution scenarios for three case study cities in Latin America: Mexico City, Mexico; Santiago, Chile; and São Paulo, Brazil. For each city, hypothetical emissions scenarios were developed to estimate how current and future patterns of fossil fuel use could affect air quality. Published health effects literature was used to estimate the number of health events for morbidity and mortality that would be avoided if modest control policies were adopted, as compared to a business-as-usual scenario. The economic benefits of the control policy scenario were estimated for the adverse health effects avoided.

2. Case study cities

Each of the three case study cities has present-day high levels of air pollution despite control measures. Efforts to curb Mexico City’s air pollution in recent years reversed the trend of increasing pollution observed during the 1980s and 1990s. However, PM10 and ozone levels are still far above Mexican air quality standards and remain a serious public health threat (Escurra and Mazari-Hirait, 1996). From 1997 to 2003, PM10 levels averaged 60.2 µg/m3 and ozone averaged 105.1 ppb (Cifuentes et al., 2005). The Mexican ozone standard was exceeded on 330 days in 1990 and on 280 days in 2002. The PM10 standard was exceeded on 112 days in 1995 and on 5 days in 2002.

Brazil is one of the most rapidly growing countries in the world, with a quickly developing transportation network. The São Paulo metropolitan area includes over 10 million residents and is responsible for about a quarter of the country’s cars, trucks, and buses. The climate of São Paulo promotes frequent thermal inversions that restrict the dispersal of pollutants during the winter period of June to August. NOx, particulates, O3, and CO levels regularly exceed WHO recommendations in most of the metropol-

tan area. The average concentrations from 1997 to 2003 were 49.0 µg/m3 for PM10 and 43.1 ppb for ozone (Cifuentes et al., 2005).

Santiago has high levels of air pollution, due to its 900,000 motor vehicles, geography, and climate. Measures to reduce pollutant emissions have been underway since the early 1990s, with the annual average level of PM10 falling from 108 µg/m3 in 1990 to 82 µg/m3 in 1998, while PM2.5 (PM with an aerodynamic diameter no larger than 2.5 µm) dropped from 65 to 39 µg/m3 in the same period. The Decontamination Plan started in 1997 by the Chilean National Environmental Commission aims to reach the primary standard for PM10 (50 µg/m3 annual average) by the year 2011.

Numerous studies have identified relationships between air pollution and health in these three urban centers. For example, in Mexico City PM has been associated with mortality (Borja-Aburto et al., 1997, 1998; Castillejos et al., 2000), including infant mortality (Loomis et al., 1999) and heart rate variability in the elderly (Holguin et al., 2003). Ozone levels have been linked to mortality (O’Neill et al., 2004), higher rates of school absenteeism for children (Romieu et al., 1992), emergency room visits for asthma (Romieu et al., 1995), and upper respiratory symptoms (Sanchez-Carrillo et al., 2003).

Higher levels of air pollution in São Paulo have been associated with several health outcomes, including low birth weight (Gouveia et al., 2004), children’s emergency room visits (Lin et al., 1999) and hospital admissions (Braga et al., 1999, 2001; Saldive et al., 1994; Gouveia and Fletcher, 2000a), emergency room visits for the elderly (Martins et al., 2002), ischemic cardiovascular emergency room visits (Lin et al., 2003), and mortality (Saldive et al., 1995; Gouveia and Fletcher, 2000b; Botter et al., 2002; Martins et al., 2004) including children’s mortality (Connellão et al., 2001). Many studies have identified a relationship between air pollution in Santiago and mortality (Ostro et al., 1996; Cifuentes et al., 2000a,b), medical visits for children (Ostro et al., 1999), wheezing bronchitis for infants (Pino et al., 2004), and respiratory-related emergency room visits for children (Ilabaca et al., 1999).

This research quantifies how air pollution control policies could impact human health in these three cities. Using hypothetical emissions control policies and concentration–response functions from epidemiological studies, we estimated the number of selected health outcomes that could be avoided over a 20-year period under a control policy scenario and then estimate the economic value of these health endpoints.

3. Materials and methods

3.1. Emissions scenario development

Annual pollution levels for PM10 and ozone from 2000 to 2020 were estimated for Santiago, Mexico City, and São Paulo under two emissions scenarios: a business-as-usual scenario and a control policy. The
business-as-usual scenario represents present air pollutant emissions and trends and reflects current and pending proposals to abate air pollution directly. For the business-as-usual scenario, emissions levels for Mexico City assume that improvements in the polluting characteristics of new cars are at least partly offset by the rising number of vehicles and that industrial emissions may rise at the expected growth rate of the Metropolitan Region of Mexico City economy. Air pollution reduction policies implemented in São Paulo in the past decade were countered by sizeable increases in the vehicle fleet. Given recent trends in Santiago’s pollution levels, the business-as-usual scenario for this city assumes that air pollution levels would meet the targets of the Decontamination Plan (i.e., compliance with Chilean standards) by 2011 and continue to decline.

The control policy scenario considers the impact of air pollution mitigation measures on the emissions of primary pollutants and the consequent impacts on secondary pollutants. This scenario assumes the application of readily available control technologies to mitigate emissions in energy, transport, residential, and industrial emission sectors. The control policy was partially based on a previous Chilean study, which demonstrated that changes in fuel use and increased energy efficiency could reduce emissions of greenhouse gases and other pollutants without significant economic cost (Cifuentes et al., 2000c, 2001a,b). This Chilean study modeled a gradual 13% reduction in emissions, resulting in approximately a 10% reduction in air pollutant concentrations for PM$_{10}$ and O$_3$ over a 20-year period. The results were consistent with another study that focused on Chile (Dessus and O’Conner, 1999).

Estimates under an air pollution control policy assuming gradually reduced concentrations each year were derived reaching a 10% reduction in major pollutants below 2000 levels by 2020 (Cifuentes et al., 2001a,b). This analysis assumes that the three Latin American cities have similar mixes of fuel and technology and that pollution reductions in Mexico City and São Paulo will be similar to those that have taken place in Chile. For the year 2020, the control policy has lower projected concentrations for Mexico City, Santiago, and São Paulo by 5.2, 4.6, and 5.2 μg m$^{-3}$ for the annual average PM$_{10}$, respectively. The annual average daily 1-h maximum ozone concentration is estimated to be lower by 11.0, 2.7, and 4.2 ppb in the year 2002 for Mexico City, Santiago, and São Paulo, respectively. The control policy scenario presented here is meant to serve as an example of a relatively conservative air pollution mitigation strategy and not a comprehensive analysis of a particular policy; other strategies would also benefit public health. This research provides a framework that could be used to investigate the effects of other emission scenarios.

### 3.2. Health effects estimation methods

While multiple air pollutants, including PM, SO$_2$, CO, O$_3$, and nitrogen dioxide (NO$_2$), have been linked with adverse human health, the annual average PM$_{10}$, respectively. The annual average daily 1-h and 4.2 ppb in the year 2002 for Mexico City, Santiago, and São Paulo, maximum ozone concentration is estimated to be lower by 11.0, 2.7, and 4.2 ppb in the year 2002 for Mexico City, Santiago, and São Paulo, respectively. The control policy scenario presented here is meant to serve as an example of a relatively conservative air pollution mitigation strategy and not a comprehensive analysis of a particular policy; other strategies would also benefit public health. This research provides a framework that could be used to investigate the effects of other emission scenarios.

The COI is the sum of lost productivity and medical costs. It incorporates lost wages and direct medical expenses and is not a measure of individual or social welfare as it does not address discomfort and pain among other factors. The WTP method aims to measure what individuals would be willing to pay in exchange for improved health. COI estimates are typically much lower than WTP estimates. The WTP approach is based on tradeoffs between health and wealth or income. WTP valuation studies uncover actual tradeoffs (revealed preferences) or ask participants to make hypothetical decisions with regard to tradeoffs (stated preferences). WTP estimates were converted to the value of a statistical life (VSL) based on the risk change being valued. Economic values for both approaches were based on a literature review of COI and WTP studies. Economic values from studies in Latin America were used, where possible, with appropriate income ratios to transfer values among cities.

The primary sources of data were valuation studies conducted in São Paulo, Mexico City, Santiago, and Buenos Aires (Cifuentes et al., 2000b, 2005; Conte Grand et al., 2002). For health endpoints for which no Latin American values were available, United States values were used with income adjustment factors (Cifuentes et al., 2005). US values were
lost productivity values were estimated using the average daily salary for each city. The length of hospital stay was estimated from data for Santiago and Mexico City.

3.4. Sensitivity analysis

This work necessitates several assumptions including population growth, air pollutant concentrations in future years, concentration-response functions, and the economic value of avoided health outcomes. A complete sensitivity analysis would incorporate a range of pollution levels, multiple concentration-response functions derived from different epidemiological studies, and several methods for estimating the economic value of averted health consequences. We present the results from two economic valuation approaches, WTP and COI, which provide some gauge of how different economic valuation methods would affect results. A large number of epidemiological studies have not been conducted for all health endpoints. WTP estimates were calculated for avoided hospital admissions for cardiovascular and respiratory causes, respiratory emergency room visits, restricted activity days, chronic bronchitis, and premature mortality for infants and adults. The COI method incorporated the health effects listed above and children’s medical visits and hospital admissions, work loss days, and asthma attacks.

<table>
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<tr>
<th>Health endpoint</th>
<th>Study location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mortality</strong></td>
<td></td>
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<tr>
<td>Infant (&lt;1 year)</td>
<td>Mexico City</td>
<td>Loomis et al., 1999</td>
</tr>
<tr>
<td>Adult</td>
<td>United States</td>
<td>Pope et al., 2002</td>
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<tr>
<td><strong>Medical visits</strong></td>
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<tr>
<td>Children’s medical visits (3 to 15 years)</td>
<td>Santiago</td>
<td>Ostro et al., 1999</td>
</tr>
<tr>
<td>Hospital admissions (cardiovascular)</td>
<td>United States, Canada</td>
<td>Pooled from Burnett et al., 1995; Schwartz and Morris, 1995; Schwartz 1997; Morris and Naumova, 1998; Linn et al., 2000</td>
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<tr>
<td>Hospital admissions (respiratory)</td>
<td>United States, Italy, France, England, Canada, The Netherlands</td>
<td>Pooled from Thurston et al., 1992, 1994; Burnett et al., 1995; Abbey et al., 1995; Dab et al., 1996; Ponce de Leon et al., 1996; Schouten et al., 1996; Schwartz et al., 1996; Vigotti et al., 1996; Linn et al., 2000</td>
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<td>Children’s hospital admissions (respiratory, &lt;13 years)</td>
<td>São Paulo</td>
<td>Braga et al., 1999</td>
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<td>Emergency room visits (respiratory)</td>
<td>Mexico, United States, Canada</td>
<td>Pooled from Samet, 1995; Delfino et al., 1997; Atkinson et al., 1999; Damakos et al. (unpublished data)</td>
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<td><strong>Bronchitis and asthma</strong></td>
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<td>Asthma attacks</td>
<td>Los Angeles</td>
<td>Whittemore and Korn, 1980</td>
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<tr>
<td>Acute bronchitis</td>
<td>United States</td>
<td>Dockery et al., 1989</td>
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<td>Chronic bronchitis</td>
<td>United States</td>
<td>Schwartz, 1993</td>
</tr>
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<td><strong>Activity effects</strong></td>
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<tr>
<td>Restricted activity days (18 to 65 years)</td>
<td>United States</td>
<td>Ostro, 1987</td>
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<td>Work loss days</td>
<td>United States</td>
<td>Ostro, 1987</td>
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Table 2

<table>
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<th>Health endpoint</th>
<th>Study location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mortality</strong></td>
<td>Santiago</td>
<td>Cifuentes et al., 2000a</td>
</tr>
<tr>
<td></td>
<td>England, Mexico, United States, Europe</td>
<td>Pooled from Anderson et al., 1996; Moolgavkar and Luebeck, 1996; Verhoeff et al., 1996; Ito and Thurston, 1996; Kelsall et al., 1997; Borja-Abarzu et al., 1997, 1998; Touloumi et al., 1997; Hoek et al., 1997</td>
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<tr>
<td><strong>Medical visits</strong></td>
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<td></td>
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<tr>
<td>Children’s hospital admissions (&lt;5 years)</td>
<td>São Paulo</td>
<td>Gouveia and Fletcher, 2000a</td>
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<tr>
<td>Hospital admissions (respiratory)</td>
<td>United States, Canada</td>
<td>Pooled from Thurston et al., 1992, 1994</td>
</tr>
<tr>
<td>Emergency room visits (respiratory)</td>
<td>Mexico, Canada</td>
<td>Pooled from Delfino et al., 1997; Téllez-Rojo et al., 1997; Burnett and Cakmak, 1998</td>
</tr>
<tr>
<td><strong>Asthma attacks</strong></td>
<td>Los Angeles</td>
<td>Whittemore and Korn, 1980</td>
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*Used for Mexico City and São Paulo.
outcomes for this region; therefore sensitivity analysis using different concentration–response estimates is problematic.

To obtain approximate estimates of how the assumptions could affect results, we repeated the analysis under the following conditions: (1) concentration–response (C–R) functions derived from the epidemiological studies at their 95% upper bound, (2) concentration–response functions at their 95% lower bound, and (3) a lower benefits scenario with 20% decreases in the annual population growth rate, the economic value of health endpoints, concentration–response effect estimates, and the rate of decline of air pollution levels in the control policy scenario. The first two sensitivity analyses incorporate uncertainty from the epidemiological studies only, whereas the third sensitivity analysis varies other factors also. These simplistic approaches do not provide a full sensitivity analysis but do provide some perspective on the range of possibilities and establish a framework for future analysis.

4. Results

For each case study city, the control policy scenario was estimated to achieve significant health benefits from lowered pollution. The number of health effects that would be avoided by the control policy scenario, as compared to the business-as-usual scenario, cumulative from 2000 to 2020 for each city, is provided in Table 3. Results across cities differ based on their population, age distribution, population growth, concentration–response functions, and baseline morbidity and mortality rates. Mortality estimates for Santiago are lower, which is a combination of the smaller population in this city (less than 30% of Mexico City’s population) and the smaller difference in concentrations between the business-as-usual and the control policy scenarios.

In the year 2020 alone, the reduced emissions could avert over 3300 deaths in Mexico City, over 500 respiratory hospital admissions in Santiago, and almost 80,000 asthma attacks in São Paulo. Across all three cities, more than 3700 infant deaths and almost 153,000 adult deaths are estimated to occur over the 20-year period if current pollution practices continue as compared to the control policy scenario. The impact on morbidity is also large, with over 60,000 avoidable respiratory hospital admissions, more than 300,000 children’s medical visits, and over 700,000 respiratory emergency room visits. The elevated pollution levels under the business-as-usual scenario result in over 4 million avoidable asthma attacks, almost 24 million restricted activity days, and over 8 million work loss days in the three cities.

The economic value of these avoided health impacts was estimated using two methods, each of which estimates benefits for only a subset of the health outcomes considered. In the first year alone of the control policy scenario, almost $567 million (US) in health effects could be saved for the three cities combined, as estimated with the WTP approach. The first year of savings using the COI approach is almost $71 million. By 2020, these reductions in air pollution could save approximately $21 billion (COI) to $165 billion (WTP) in avoided health outcomes across the three cities. Much of the economic value comes from averted premature mortality, especially from chronic exposure to PM, as has been found in other studies (e.g., USEPA, 1997, 1999). Avoided mortality accounts for almost half of the overall economic benefit from the COI approach and about three quarters of the total benefit using the WTP approach.

Sensitivity analyses revealed that even when the assumptions are relaxed sizeable health and economic benefits are predicted from the control policy scenario. Table 4 shows the number of health impacts avoided and the economic value for the original scenarios and the three sets of assumptions described in Section 3.4. When uncertainty from the epidemiological studies is included, the lower bound of benefits is still over $12 billion for the COI approach and about $82 billion for the WTP approach. When population growth, concentration–response effect

<table>
<thead>
<tr>
<th>Health endpoint</th>
<th>Mexico City</th>
<th>Santiago</th>
<th>São Paulo</th>
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</thead>
<tbody>
<tr>
<td><strong>Mortality</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Adult</td>
<td>33,084</td>
<td>6733</td>
<td>113,165</td>
</tr>
<tr>
<td>Infant (&lt;1 year)</td>
<td>2648</td>
<td>385</td>
<td>735</td>
</tr>
<tr>
<td><strong>Medical visits</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Children’s medical visits (3 to 15 years)</td>
<td>113,623</td>
<td>51,043</td>
<td>138,572</td>
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<tr>
<td>Hospital admissions (cardiovascular)</td>
<td>2919</td>
<td>997</td>
<td>1449</td>
</tr>
<tr>
<td>Hospital admissions (respiratory)</td>
<td>46,275</td>
<td>6067</td>
<td>10,945</td>
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<tr>
<td>Children’s hospital admissions (&lt;13 years for PM10, &lt;5 years for O3)</td>
<td>4836</td>
<td>3675</td>
<td>5563</td>
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<tr>
<td>Emergency room visits (respiratory)</td>
<td>537,826</td>
<td>73,125</td>
<td>102,331</td>
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<td><strong>Bronchitis and asthma</strong></td>
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<td>Asthma attacks</td>
<td>2,988,077</td>
<td>481,109</td>
<td>817,064</td>
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<td>Acute bronchitis</td>
<td>78,528</td>
<td>25,426</td>
<td>38,384</td>
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<td>Chronic bronchitis</td>
<td>28,371</td>
<td>7929</td>
<td>11,603</td>
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<td><strong>Activity effects</strong></td>
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<tr>
<td>Restricted activity days (18 to 65 years)</td>
<td>12,722,033</td>
<td>4,347,564</td>
<td>6,852,601</td>
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<tr>
<td>Work loss days</td>
<td>4,412,424</td>
<td>1,507,880</td>
<td>2,376,710</td>
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estimates, decline in air pollution levels in the control policy, and economic values for specific health endpoints are all relaxed (sensitivity analysis scenario 3), the benefit is still almost $16 billion for the COI approach and over $129 billion for the WTP method.

5. Discussion

Results demonstrate that current emissions trends create an enormous health burden in three of the world’s largest and fastest growing urban zones in Latin America. With relatively modest air pollution control, such as policies incorporating existing technologies, numerous health effects and the subsequent economic impact could be prevented.

Analyzing the total burden on human health from ambient air pollution remains challenging, given the uneven nature of information and the wide range of uncertainties characterizing many parts of the process. In this research, several assumptions were made, such as the use of concentration–response functions derived from studies outside the cities of interest. The pollution and populations in these cities may differ. For instance, the PM in various cities may have dissimilar chemical compositions. While many characteristics of PM have been associated with adverse health outcomes, the specific components that are harmful are not well understood.

The true relationship between PM and health may depend on the PM’s chemical composition, in addition to more widely studied features such as size. For instance, the effect of PM on mortality in the US differs by season and region, with the strongest effect in the northeast (Dominici et al., 2003; Peng et al., 2005). It is possible that PM in the three case study cities differs from the pollution in the US cities used for the concentration–response functions for PM. Also, data from a single city was used for PM effects across the other two cities for several endpoints (e.g., children’s medical visits), and the PM composition could vary among the three cities based on climate and emissions patterns.

Several efforts have characterized the particulate air pollution in these three cities (e.g., Koutrakis et al., 2005; Miranda et al., 2000; Vega et al., 2002, 2004). For example, a study of winter PM in Mexico City found that sulfate concentrations were twice that of nitrate and that only about a third of ammonium sulfates was formed from within the urban study area (Chow et al., 2002). Source apportionment revealed that summer and winter PM have similar source patterns in São Paulo and that automobile and soil dust are the main sources of air pollution in the city (Cantanho and Artaxo, 2001). The three main sources contributing to fine PM in São Paulo are vehicles, secondary carbon, and sulfates (Alonso et al., 1997). Santiago PM contains large concentrations of elements such as Pb, Br, and Cl that are tracers for vehicular emissions (Artaxo et al., 1999). Transportation emissions contribute a significant fraction of PM10 in all three cities (O’Ryan and Larraguibel, 2000). However, there are no current PM concentration–response functions available for each health point and city, much less effect estimates that adequately capture the true relationship between health.

### Table 4

<table>
<thead>
<tr>
<th>Health endpoint</th>
<th>Original scenarios</th>
<th>(1) C-R lower 95% bound</th>
<th>(2) C-R upper 95% bound</th>
<th>(3) Lower benefits scenario</th>
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<tr>
<td><strong>Mortality</strong></td>
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<td>Adult</td>
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<td>1437</td>
<td>6101</td>
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<td><strong>Medical visits</strong></td>
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<td>Children’s medical visits</td>
<td>303,238</td>
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<td>Hospital admissions (respiratory)</td>
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<td>23,922,198</td>
<td>21,079,332</td>
<td>26,765,060</td>
<td>14,909,407</td>
</tr>
<tr>
<td>Work loss days</td>
<td>8,297,014</td>
<td>7,024,800</td>
<td>9,569,072</td>
<td>5,171,078</td>
</tr>
<tr>
<td><strong>Economic valuation (billions)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COI approach</td>
<td>$20.7</td>
<td>$12.3</td>
<td>$51.0</td>
<td>$15.8</td>
</tr>
<tr>
<td>WTP approach</td>
<td>$164.6</td>
<td>$82.0</td>
<td>$434.3</td>
<td>$129.4</td>
</tr>
</tbody>
</table>

*a*Health outcomes included in the WTP and COI estimates.

*b*Health outcomes included in the COI estimates.
effects and PM components within each city. The study design of this research could be applied should such concentration–response functions become available.

Ideally this analysis would use more precise estimates of the relationship between pollution and human health including the differences among cities, the pollution impacts of various emissions scenarios, and the changes in age distributions in the cities. However, such complete data are not available. The sensitivity analyses provide some insight into how results would be altered if assumptions with regard to population growth, economic value of health outcomes, concentration–response estimates, and pollutant concentrations were altered; however, other scenarios could also be investigated. This work is intended to generate an approximation of the likely health and related economic impacts that result from air pollution in three case study Latin American cities and to establish a framework that could be applied to investigate other scenarios.

The estimates provided here include only a subset of urban air pollutants and health outcomes, so they do not reflect the full extent of health benefits from air pollution control policies. For instance, we did not include all of the effects of air pollution, such as low birth weight (Gouveia et al., 2004) and cancer (Cohen, 2000; Pope et al., 2002; Naftad et al., 2003). Further, other harms of air pollution were not included, such as ecosystem damage, material decay, and visibility, which would also add to the economic burden.

This research uses concentration–response functions from a cohort study for the relationship between PM and mortality and considers only the short-term effects of ozone on mortality. Effect estimates from cohort studies for PM have typically been larger than those for time-series studies. The effect estimate from the PM study used for chronic exposure (Pope et al., 2002) is larger than city-specific estimates for acute exposure for Santiago (Cifuentes et al., 2000a), Mexico City (Castillejos et al., 2000), or São Paulo (Gouveia and Fletcher, 2000b). Air pollution can affect mortality in three distinct pathways: (1) increased risk of chronic disease resulting in frailty; (2) increased short-term mortality risk among the frail population; or (3) increased risk of both the underlying diseases leading to a weakened condition and the short-term mortality risk among that frail population (Künzli et al., 2001). Concentration–response results from cohort studies reflect all three pathways, whereas time-series studies do not assess the first pathway. Therefore it is preferable to use estimates from cohort studies rather than time-series studies (Künzli et al., 2001). The results presented here are conservative if long-term exposure to ozone also affects risk of mortality.

This work estimates only the local and short-term impacts of air pollution control policies; however, the fossil fuel technologies that affect concentrations of air pollutants can also influence longer-term climate and weather patterns through greenhouse gases. Therefore short- and long-term air pollution problems are inherently coupled, as the same activities that contribute to global warming also directly threaten human health in the short term. Lower air pollution would produce two types of health benefits: (1) immediate benefits tied with lower pollution levels and (2) potential benefits of reduced levels of air pollution associated with mitigated climate change such as lower temperature (e.g., lower levels of ozone because the chemical reactions that form tropospheric ozone are driven by sunlight and high temperatures) (Davis, 1997; Cifuentes et al., 2001a,b). Thus, the control policy scenario explored here would likely contribute to lower greenhouse gas emissions and improved air quality in the short term.

This research supports earlier efforts that estimated the short-term regional effects on public health that may arise from current patterns of fossil fuel use and how these health risks could be mitigated under various policy scenarios (Cifuentes et al., 2001a,b; West et al., 2004). One global estimate looked solely at PM-related mortality in nine major regions of the world, based on studies developed largely in industrialized countries. The study considered the avoidable deaths from 2000 and 2020, comparing health effects under current policies to a scenario proposed by the European Union in 1995, which assumed that by 2010 greenhouse gases would be 15% below business-as-usual conditions in 1990 for the industrial world and 10% below business-as-usual 2010 levels for Non-Annex I countries (Davis, 1997; Working Group on Public Health and Fossil-Fuel Combustion, 1997). Based solely on projected changes in PM and associated declines in mortality by 2020, approximately 700,000 deaths each year could be avoided by adaptation of the European Union scenario.

A US assessment of four proposed mitigation policies charted a broad array of potential public health consequences resulting from changes in exposure to PM_{2.5} under several scenarios: (1) a $25/tonC carbon tax, assuming that much of the country met the revised National Ambient Air Quality Standards (NAAQS), including seasonal controls of NO\textsubscript{x} in 37 states east of the Mississippi River and a 50% reduction in SO\textsubscript{2} emissions beyond the requirements of the Clean Air Act; (2) a $25/tonC carbon tax, with only 22 states imposing additional NO\textsubscript{x} controls; (3) a $25/tonC carbon tax, without any additional SO\textsubscript{2} control; and (4) a $56/tonC tax, with partial attainment of the NAAQS (Abt Associates, Inc. 1999). The analysis showed that these emissions reduction policies would have enormous health benefits. For example, under Scenario 4 over 2000 adult premature deaths, 700 respiratory hospital admissions for the elderly, 520,000 work loss days, and 2.7 million days with minor restriction in activity could be avoided.

A World Bank study estimated that a 10% reduction in ozone and PM\textsubscript{10} levels in Mexico City would save about $760 million (US) each year (Cesar et al., 2002), which is much larger than our estimates for Mexico City for the first year. The Cesar et al. work explored additional health
outcomes such as cough symptoms for asthmatics and chronic cough in children. A recent study by Cifuentes et al. (2005) explored the health and economic burdens of urban air pollution in 40 Latin American cities. This study, which in some cases used higher concentration–response estimates than those used here, estimated that a 10% reduction in PM levels would save between 273 and 1189 lives annually in Mexico City based on the current population. The 40 cities investigated included our case study cities; however, none of these 3 cities were in the top 10 cities anticipated to benefit the most from reductions in air pollution. This implies that, should our work be extended to additional cities, the control policy scenario would have an even larger impact in some other areas. The Cifuentes et al. (2005) and Cesar et al. (2002) studies suggest that the estimates presented here are conservative.

This work shows that the cumulative health effects and economic burden for the next two decades under current emissions patterns is exceedingly high for each of these Latin American cities. Air-pollution-related health effects can be reduced through policies that curb emissions, many of which would also have long-term benefits through mitigated climate change. Among measures that can be undertaken to achieve these reductions are the use of cleaner fuels, improved public transportation systems, and programs to increase public awareness. Results from this research indicate that even modest policies aimed at mitigating air pollution can provide a broad range of immediate benefits on public health and subsequent economic benefits.

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