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Analyzing the cost effectiveness of Santiago, Chile's policy of using urban forests to improve air quality

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Abstract

Santiago, Chile has the distinction of having among the worst urban air pollution problems in Latin America. As part of an atmospheric pollution reduction plan, the Santiago Regional Metropolitan government defined an environmental policy goal of using urban forests to remove particulate matter less than 10 μm (PM_{10}) in the *Gran Santiago* area. We used cost effectiveness, or the process of establishing costs and selecting least cost alternatives for obtaining a defined policy goal of PM_{10} removal, to analyze this policy goal. For this study, we quantified PM_{10} removal by Santiago's urban forests based on socioeconomic strata and using field and real-time pollution and climate data via a dry deposition urban forest effects model. Municipal urban forest management costs were estimated using management cost surveys and Chilean Ministry of Planning and Cooperation documents. Results indicate that managing municipal urban forests (trees, shrubs, and grass whose management is under the jurisdiction of Santiago's 36 municipalities) to remove PM_{10} was a cost-effective policy for abating PM_{10} based on criteria set by the World Bank. In addition, we compared the cost effectiveness of managing municipal urban forests and street trees to other control policies (e.g. alternative fuels) to abate PM_{10} in Santiago and determined that municipal urban forest management efficiency was similar to these other air quality improvement measures.

Keywords: Cost-effective analysis; Urban forest management; Air pollution abatement; Street trees; Ecosystem services

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1. Introduction

Urban forests (trees, shrubs, and grass) provide many ecosystem services that benefit human well-being (Beckett et al., 1998; McPherson et al., 1999; Nowak et al., 2002; Scott et al., 1998; Ulrich, 1986; WRI, 2001; Yang et al., 2005). Some of these services include improved human health, community empowerment, climate modification, recreational benefits, wildlife habitat, wood, food, and aesthetics (Dwyer et al., 2003; Gutiérrez, 2000; Intendencia Región Metropolitana, 1987; Murray, 1996a, b; Ulrich, 1986; World Bank, 1994). Several Latin American cities, among them Santiago, Chile; Mexico City, Mexico; and São Paolo, Brazil, are integrating trees and other vegetation as part of urban environmental improvement programs, policies, and measures.

Santiago, Chile has the distinction of having among the worst urban air pollution problems in Latin America despite having a steady improvement in air quality over the last 10 years (SESMA, 2000; World Bank, 1994, 1997). The city is located 450–900 m above sea level in a basin surrounded by 2000 m tall mountain ranges. These geographic conditions contribute to thermal inversions and restricted air flow through the basin that aggravate air

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quality problems. The *Gran Santiago* airshed comprises a study area of 967 km^2 located in the northernmost section of a basin referred to as the *Valle Central* and contains well over 5 million residents—nearly 40% of Chile's population. The *Gran Santiago* Metropolitan Area is Chile's administrative, cultural, and industrial center that encompasses residential areas, industrial and commercial districts, transportation networks, agricultural lands, *espinal* shrub-lands, and Andean piedmont. Santiago's semi-arid climate and urbanized environment also poses a major limitation for the establishment of trees in Santiago (Escobedo, 2004; Escobedo et al., 2006). As a result, the current urban forest cover has to be attributed to active management by its human inhabitants (Escobedo, 2004).

Santiago has an existing *Plan de Prevención y Descontaminación Atmosférica* (PPDA; Atmospheric Prevention and Decontamination Plan) that is part of the Chilean Environmental Commission's *Ley de Bases Generales del Medio Ambiente* (Law of General Environmental Baselines) that defines a policy goal of using street trees and green areas to reduce the emissions of particulate matter less than 10 μm (PM_{10}) in the *Gran Santiago* metropolitan region (CONAMA, 1997, 2001; CONAMA-RM, 2002).[1] Street trees are trees within the right of way or easement of any major or minor thoroughfare. Green areas refer to parks, plazas, large medians, squares or any vegetated public or open access area administered by the municipality or other public entity. Laws and ordinances have established the administrative infrastructure for the management of Santiago's street trees and green areas under the jurisdiction of Santiago's 36 *comuna's*, departments of *Aseo y Ornato* (Waste management and landscaping) (Ceballos Ibarra, 1997; Escobedo, 2004; Escobedo et al., 2006). A *comuna* is an autonomous municipality with its own mayor, council, budget and department of *Aseo y Ornato*. As there is no legal definition of an urban forest in either of these laws or ordinances, for convenience we will describe a municipal urban forest (MUF) as trees, shrubs, and grass (i.e. street trees and green areas) whose management is under the jurisdiction of Santiago's 36 *comunas* and an urban forest as all trees, shrubs, and grass within the *Gran Santiago* metropolitan region.

The 36 *comuna*s are currently allocating part of their municipal budgets to manage their MUFs. However, we found no published analysis examining whether MUF management in Latin America is in fact a cost-effective policy for reducing PM_{10}. McPherson et al. (1998) reported that planting residential shade trees for air quality benefits is not cost effective in California, USA. However, Nowak et al. (1998) rebut this conclusion based on the limited scale of analysis and methods used in McPherson et al. (1998) study. The focus of this study was on municipal urban forests because private expenditures on tree maintenance were not readily available given the time frame and budget of this research. Thus, the research question investigated by this study is whether managing Santiago's MUFs are cost effective in reducing PM_{10} concentrations.

2. Materials and methods

2.1. Policy analysis model

To analyze the effectiveness of urban forest management for air quality improvement, any analysis model must compare urban forest management with other public investment alternatives. By using this type of approach as a component of the urban forest-decision making framework; economic, social, political, and environmental factors can be weighed against one another and in doing so assist the decision maker in selecting the best alternative. The cost-effective analysis policy model used in this study is a specific type of approach in which the goal of a policy is defined, the threshold costs of obtaining that goal are established, and then the most efficient alternatives are selected (Field, 1997; Larson et al., 1999). As opposed to a cost-benefit analysis, a cost-effective analysis by its more limited frame of reference permits an analyst to compare and advocate policies by quantifying costs in monetary units and effects in units of functions or services (Dunn, 1981; Poister, 1978; Portney, 2000). In doing so the analyst determines *how* the resources should be used and not *whether* they should be used to meet a policy objective in a technologically efficient manner (Larson et al., 1999; Poister, 1978).

Estimating the cost effectiveness of Santiago's policy to use MUFs to remove PM_{10} will require developing a quantitative relationship between the urban forest's ability to remove PM_{10} and its management costs. Determining a direct relationship between MUF management and air quality can be difficult (Brimblecombe, 2001; Krupnick and Portney, 1991). However, a vegetation cover-atmosphere process can be used as a link between MUF cover and air quality. The amount of pollution that vegetation cover removes per unit time is a function of dry deposition velocity (V_d meters per second (m/s)) or the rate at which vegetation cover "removes" a pollutant from the atmosphere given an ambient pollutant concentration (C grams per cubic meter (g/m^3)). By calculating the dry deposition velocity of MUFs and determining ambient pollutant concentration, pollutant flux (F) or removal can be calculated ($F = V_d C$ ($g/m^2/s$)) (Davidson and Wu, 1990; Fowler, 2002; Lovett, 1994; McPherson et al., 1998; Nowak et al., 2002; Scott et al., 1998). Therefore, given that the existing MUF cover in Santiago is the result of purposeful management, by quantifying Santiago's MUFs structure and modeling its ability to remove PM_{10} combined with the management costs of maintaining that cover we will be able to estimate the costs of abating PM_{10}. If this cost estimate is less than a threshold described by the World Bank (1994), then managing Santiago's MUFs are cost effective in reducing PM_{10} concentrations.

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[1] The PPDA policy does not mention any other pollutants, hence only PM_{10} will be analyzed.

Table 1
Santiago demographics

Socioeconomic strata	Area (km^2)	Average annual per capita income (US\$2000)	Population (2000)[a]	Population density (pop/km^2)
High	164.9	10 000	773 633	4692
Medium	370.3	4000	1 924 767	5198
Low	431.9	1250	2 823 864	6538
Total	967.1		5 522 264	5710

Source: ICCOM-Novaction (2004) and Instituto Nacional de Estadistica-Chile statistics.
[a] Includes both rural and urban inhabitants within the *comunas*.

Santiago's 36 *comunas* are self-governing municipalities with their own mayor, council, municipal budgets, and MUF management programs. Their demographic and socioeconomic characteristics are different. Consequently, they were divided into three socioeconomic strata based on ICCOM-Novaction (2004) classifications (Escobedo et al., 2006). *Comunas* with 25% of their households in the highest three classifications were defined as the high socioeconomic stratum. *Comunas* with 50% of their household in the middle two classifications were defined as the medium socioeconomic stratum. *Comunas* with 25% of their household in the lowest two classifications were defined as the low socioeconomic stratum (see Table 1 and Fig. 1) (Escobedo, 2004).

2.2. *Quantifying urban forest structure*

To quantify Santiago's urban forest structure 200, 0.04 ha random, permanent, circular plots were distributed among the three socioeconomic strata proportional to tree cover area: 74, 62, and 64 plots were allocated to the high, medium, and low socioeconomic strata, respectively following standard UFORE methods (Escobedo, 2004; Escobedo et al., 2006). This resulted in a sampling intensity of less than 1% of each stratum's urban forest cover. The plots centers were located by applying a random number generator of x and y coordinates per stratum using a geographic information system (GIS: ARCVIEW 3.2 with spatial analyst extension) and 1:10 000 black and white, digital ortho-photographs across public and private property within the study area.[2] When plot access permission was not given or the plot was inaccessible (approximately 5% of all plots), the plot was relocated in the immediate area within the same land use and general surface cover characteristics. Specifically, the next parcel in a clockwise direction was selected until access was possible and marked on ortho-photograph. The plot was relocated in the same relative position on the parcel as the original plot.

The urban forest field data were collected during January and February 2002. The data recorded from each plot included land use, percent grass, and other ground cover. Shrubs were identified to the species level and measured for height, percent of shrub mass volume occupied by leaves, and percent of total shrub area occupied by the shrub mass. Trees whose stem center was located within the plot and had a minimum diameter at breast height of 2.54 cm, had the following information recorded: species, number of stems, height, height to base of live crown, crown widths along a north–south axis and an east–west axis, percent dieback, percent foliage density, and indication if the tree was located on a street or green area and hence managed by the municipality or other public entity (Nowak et al., 2003; Escobedo et al., 2006). Tree, shrub, and grass cover were quantified independently thereby accounting for spatial overlap.

These data were incorporated into the Urban Forest Effects (UFORE) model to quantify urban forest structure (e.g. leaf area, leaf cover, leaf area index, evergreen leaf composition, and leaf biomass) (Nowak and Crane, 2000). The UFORE model was developed by the USDA Forest Service to quantify urban forest structure and function and aid in urban forest management. In general, the urban forests in the high socioeconomic stratum were in better condition than those in the medium and low socioeconomic strata. The medium and low socioeconomic strata were characterized by relatively larger, older, isolated trees in generally poor condition (Escobedo, 2004).

The model estimated tree density, leaf area index, leaf biomass and other parameters (Escobedo et al., 2006). For this study however, the urban forest structure parameter of interest is leaf area (m^2)[3]. Table 2 gives the MUF cover by socioeconomic strata. The low and medium socioeconomic stratum's MUF cover is greater than the high socioeconomic stratum's even with the medium and low socioeconomic stratum's urban forests in poorer condition than those in the high socioeconomic stratum. This difference is because the low and medium socioeconomic strata encompassed nearly 80% of the study area (Tables 1 and 2).

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[2] Because no ortho-photographs were available for 2 of the 36 *comunas*, only 34 *comunas* were used for this analysis. The 2 *comunas* were in the low socioeconomic stratum.

[3] Because leaf area (m^2) can easily be measured, leaf area index, tree density, and leaf type which are important parameters in pollution deposition, are not discussed in the analysis because they are already incorporated into the model (see Escobedo (2004) for discussion of the role of these parameters in pollution removal).

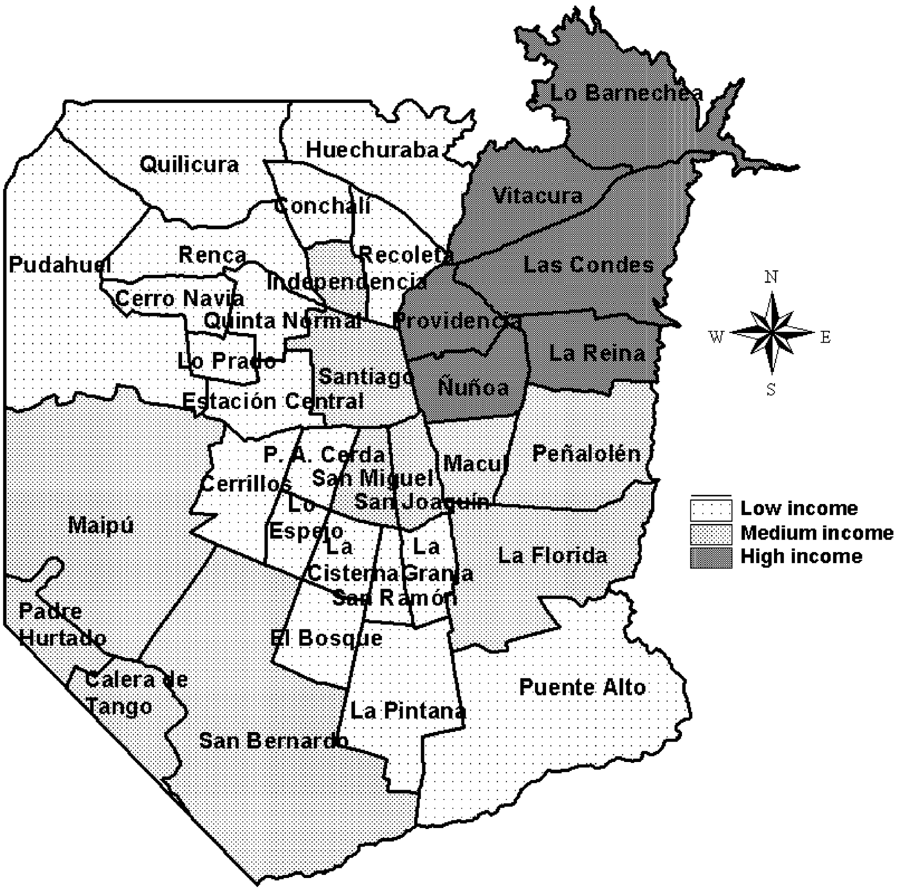

Fig. 1. *The Gran Santiago's* 36 *comunas* and three different socioeconomic strata.

Table 2
Municipal urban forest covers by socioeconomic strata

Socioeconomic strata	Tree cover[a] (m^2)	Shrub cover[b] (m^2)	Grass cover[b] (m^2)	Total MUF cover[c] (m^2)
High	12 517 620	10 487 640	26 388 000	49 393 260
Medium	17 414 804	14 515 760	55 992 400	87 922 964
Low	32 830 110	13 820 800	40 076 608	86 727 518

[a] UFORE calculated cover based on actual field measurements.

[b] The proportion of municipal shrub and grass cover was not measured in the field. Using professional judgment, municipal shrub and grass cover was assumed to be 40% of total shrub and grass cover as calculated by UFORE based on field measurements.

[c] MUF is municipal urban forest (trees, shrubs, and grass whose management is under the jurisdiction of Santiago's 36 municipalities) cover.

2.3. *Modeling PM_{10} removal rates*

Annual PM_{10} removal rates for the period July 2000–June 2001 were calculated by UFORE based on the MUF structure, hourly weather data, and hourly ambient PM_{10} concentrations.[4] The weather data were obtained from the *La Platina* weather station in the *comuna* of *La Pintana*. The MACAM-2 monitoring network (SESMA, 2000) was used to obtain hourly pollutant concentration data stratified by socioeconomic stratum. Missing hourly PM_{10} concentration data were estimated using the monthly average for the specific hour and particulate matter resuspension accounted for (Nowak and Crane, 2000). Hourly ambient PM_{10} concentrations for the high socio-

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[4] During periods of precipitation, pollution is removed via wet deposition and dry deposition is not occurring; therefore, pollution removal by urban forest cover was set to zero during periods of precipitation. The model assumes a 50% resuspension rate of PM_{10} back to the atmosphere based on Zinke (1967).

Table 3a
Annual PM_{10} removal rates for municipal urban trees, shrubs, and grass by socioeconomic strata as calculated by UFORE (July 2000–June 2001)

Socioeconomic strata	Tree removal rates ($g/m^2/yr$)[a]		Shrub removal rates ($g/m^2/yr$)		Grass removal rates[c] ($g/m^2/yr$)	
High	7.5	(2.9–11.7)[b]	8.5	(3.3–13.3)[b]	1.3	(1.2–4.7)
Medium	7.4	(2.3–11.5)	5.7	(2.2–8.8)	1.7	(0.9–4.6)
Low	8.0	(3.1–12.4)	5.8	(2.3–9.1)	1.8	(1.2–5.0)

[a] $g/m^2/yr$ denotes grams per square meter per year.

[b] Ranges are based on reported low and high deposition velocities from the literature (Nowak et al., 2002).

[c] The grass removal rates calculated by UFORE, are based on the lowest, tree dry deposition velocity from the literature (Nowak et al., 2002). The ranges are the low and high tree removal rates divided by 2.5 based on research by Shreffler (1978) for grass SO_2 deposition velocities.

Table 3b
Total annual PM_{10} removal rates for municipal urban forests by socioeconomic strata as calculated by UFORE (July 2000–June 2001)

Socioeconomic strata	Total removal rates ($g/m^2/yr$)	
High	17.3	(7.5–29.7)[a]
Medium	14.8	(5.4–24.9)
Low	15.6	(6.6–26.5)

[a] Ranges are based on the low and high deposition velocities given in Table 3a.

economic stratum were obtained from the *Las Condes* and *Providencia* MACAM-2 monitoring stations; for the medium socioeconomic stratum were obtained from *La Florida, La Paz*, and *Parque O'Higgins* MACAM-2 monitoring stations; and for the low socioeconomic stratum were obtained from the *Pudahuel, Cerrillos*, and *El Bosque* MACAM-2 monitoring stations. The mean annual ambient PM_{10} concentrations for the study period were 59.1, 78.9, and 84.4 micrograms per cubic meter ($\mu g/m^3$) for the high, medium, and low socioeconomic stratum, respectively. As a point of comparison, in 1995 the cities of Santiago, São Paolo, Bogotá, and Mexico City had average PM_{10} levels of 109, 105, 70, and 87 $\mu g/m^3$, respectively (World Bank, 1997).

The annual PM_{10} removal rates for MUFs by socioeconomic strata are shown in Tables 3a and 3b. Unfortunately, there are no grass PM_{10} deposition velocities reported in the literature. However, the estimates of grass removal rates, as reported by the UFORE model are based on tree dry deposition velocities. Shreffler (1978) states that "observations and predictions indicate the deposition velocity over a forest will be 2–3 times as great as over grass." Therefore, the grass removal ranges are the low and high tree removal rates divided by 2.5.

Annual PM_{10} removal rates for MUF in the high socioeconomic stratum were greater than for MUFs in the medium and low socioeconomic strata. There was however variability among tree, shrub, and grass removal rates for the three strata. Differences in cover, density, leaf area index, composition, and pollution concentrations among the strata also accounted for differences in pollution removal. Escobedo (2004) discusses the role of Santiago's urban forest structure in pollution removal.

2.4. Estimating municipal urban forest management costs

The MUF management cost data were collected from January to April 2002. Since all of the 36 *comunas* could not be visited, three representative *comunas* per socioeconomic stratum were selected based on existing working relations and contacts with MUF managers of those *comunas*. These *comunas* were also representative of the MUF management, social, and economic characteristics of each of their respective socioeconomic stratum. The MUF managers of the nine *comunas* were interviewed to determine budgets and expenditures and management and maintenance activities of MUF. Expenditures included annual variable and fixed investment in the management of MUFs as reported by the managers; such as the direct and indirect costs of capitol, labor, and operation activities such as administration, personnel, equipment, tree maintenance activities (e.g. pruning, planting, transplants), shrub and turf maintenance, watering, fertilization, infrastructure improvement, hazard tree damages, and sidewalk construction and repair (see Escobedo et al. (2006) for detailed list and discussion of the cost items included in this analysis).

During the interview, the managers filled out a self-administered questionnaire with the interviewer (Poister, 1978). The questionnaire was left with the manager to permit the acquisition of additional accounting information. However, most questions were answered during the interview. A final visit was scheduled to complete the questionnaire. Total municipal budgets were determined using data from nine separate *Chilean Ministerio de Planificación y Cooperación* (Chilean Ministry of Planning and Cooperation) documents (MPC, 2000).

Table 4 gives the average percent of the sampled *comuna's* annual budget allocated to MUF management by socioeconomic stratum. Due to different cost accounting methods, inconsistent definitions of costs, and differing bureaucratic levels reporting expenditures, the accuracy of cost estimates cannot be determined. For example, concurrent interviews with one *comuna's* central administrative office (*Secretaría de Planificación Comunal*) and the

Table 4
Socioeconomic strata's 2000 budget allocated to municipal urban forests management

Socioeconomic strata	Municipal urban forest management expenditure (%)		Municipal urban forest management expenditure (US$/m^2)[c]	
High	3.6[a]	(1.4–4.2)[b]	0.19	(0.08–0.23)[d]
Medium	3.8	(1.4–4.2)	0.12	(0.04–0.13)
Low	3.0	(1.4–4.2)	0.12	(0.06–0.17)

[a] The average percent of the total *comuna*'s budget allocated to street trees and green areas.

[b] Low and high ranges represent the lowest and highest percentages reported on the survey.

[c] A 2000 average monthly "Reference Exchange Rate" of 550 Ch$ = 1 US$ was used (Banco Central de Chile, 2005).

[d] Based on the lowest and highest percentages reported on the survey.

MUF management department (*Aseo y Ornato*) resulted in different line item expenditures and thus different reported expenditures for MUF management activities. To address this problem, ranges based on the low and high budget expenditures were also defined (Table 4).

2.5. Cost-effective analysis

The World Bank (1994) conducted an economic analysis of environmental problems in Chile. In their analysis of the benefits to health in Santiago from PM$_{10}$ reduction policies and measures, their results indicated that controls reducing PM$_{10}$ emission at a cost below US$ (1994) 18 000/ton/PM$_{10}$ "should be considered worthwhile and a reasonable threshold value for evaluating air pollution controls". Adjusting this value for inflation to the year 2000 results in a PM$_{10}$ control threshold value of 25 000 US$/ton/PM$_{10}$ (Banco Central de Chile, 2002). Therefore, MUF management costs of less than 25 000 US$/ton/PM$_{10}$ will be considered cost effective.

Calculating each socioeconomic stratum's MUF management costs per ton of PM$_{10}$ removed (US$/ton/PM$_{10}$) is a three-step process. First, each stratum's budget allocated to MUF management in US$ is estimated using

$$F_s = \sum_{i=1}^{S} B_{is}\beta_s, \tag{1}$$

where F_s is the budget allocated to MUF management (US$) for socioeconomic stratum s (i.e. high, medium, and low) B_{is} the ith *comuna's* total budget in socioeconomic stratum s, S the number of *comunas* in each socioeconomic stratum, and β_s the percent of the socioeconomic stratum's budget allocated to MUF management (Table 4). Second, the MUF management cost per square meter of municipal tree, shrub, and grass cover by socioeconomic stratum is estimated using

$$C_s = \frac{F_s}{TC_s + SC_s + GC_s} \quad \text{for all } s, \tag{2}$$

where C_s is the annual MUF management cost per square meter (US$/m^2) of municipal tree shrub and grass cover by socioeconomic stratum s; TC_s, SC_s, and GC_s are the municipal tree, shrub, and grass cover in square meters by socioeconomic stratum, s, respectively (Table 2). Finally, each socioeconomic stratum's MUF management cost per ton of PM$_{10}$ removed is estimated using Eq. (3):

$$A_s = \left(\frac{C_s}{TR_s + SR_s + GR_s}\right)\theta \quad \text{for all } s, \tag{3}$$

where A_s is the MUF management costs per ton of PM$_{10}$ removed (US$/ton/PM$_{10}$) for socioeconomic stratum s; TR_s, SR_s, and GR_s are the annual PM$_{10}$ removal rates by municipal trees shrubs and grass by socioeconomic stratum, s, respectively (Table 3a); and θ converts grams to metric tons.

Table 5
Cost per ton of PM$_{10}$ removed by municipal urban forest's by socioeconomic strata

Socioeconomic strata	Municipal urban forest (US$/ton/PM$_{10}$)		
High	11 185	(4350–13 050)[a]	(6515–26 150)[b]
Medium	8147	(3002–9005)	(4843–22 330)
Low	7861	(3669–11006)	(4628–18 581)

[a] Ranges based on low and high urban forestry budget allocations given in Table 4.

[b] Ranges based on low and high deposition velocities given in Table 3b.

3. Results

Table 5 shows the cost per ton of PM$_{10}$ removed by MUFs for each socioeconomic stratum. The low socioeconomic stratum's MUFs were the most cost effective at 7861 US$/ton/PM$_{10}$ and the high socioeconomic stratum's MUFs were the least cost effective at 11 185 US$/ton/PM$_{10}$. This difference was due primarily to the MUF cover (Table 2) used in calculating the MUF management cost per square meter (Eq. (2)) and the stratum's PM$_{10}$ concentration used to estimate annual PM$_{10}$ removal rates used in Eq. (3). The medium and low socioeconomic stratum's MUF cover was approximately 1.8 times larger than the high socioeconomic stratum's MUF cover

(Table 2). This caused the MUF management cost per square meter for the medium and low socioeconomic stratum's to be less than that of the high socioeconomic stratum even though the high socioeconomic stratum allocates a larger percent of their municipal budget to MUF management expenditures (Table 4). Finally, national and regional government work and tree planting programs and subsidies might be lowering overall costs in the lower socioeconomic stratum (Escobedo, 2004).

The MUFs management costs per ton of PM_{10} removed in each socioeconomic stratum were below the $25 000 threshold set by the World Bank. Due to the inaccuracies in the MUF expenditure information summarized in Table 4, we also calculated the ranges of MUF management cost per ton of PM_{10} removed (Table 5). Again, the MUF management cost per ton of PM_{10} removed in each socioeconomic stratum was below the $25 000 threshold set by the World Bank. In addition, we calculated the MUF management cost ranges per ton of PM_{10} removed based on the low and high annual PM_{10} removal rates given in Tables 3a and 3b. Using the lowest PM_{10} removal rates, the high socioeconomic stratum's MUF management cost per ton of PM_{10} removed by MUFs was greater than the World Bank threshold indicating that MUF management might not be cost effective in this socioeconomic stratum if the removal rate was at the lowest end of its expected range.

Table 6
Cost per ton of PM_{10} removed by street trees by socioeconomic strata

Socioeconomic strata	Street trees (US$/ton/$PM_{10}$)		
High	7125	(2441–13 636)[a]	(4567–18 426)[b]
Medium	9889	(3209–17 909)	(6364–25 235)
Low	8100	(3352–18 711)	(5226–20 903)

[a] Ranges based on low and high street tree budget allocations (Escobedo, 2004).

[b] Ranges based on low and high deposition velocities given in Table 3a.

Escobedo et al. (2006) also summarized management expenditure and cover information for street trees. Using this information and Eqs. (1)–(3), we examined if managing for municipally owned street trees was cost effective in reducing PM_{10} concentrations. As shown by Table 6, the management of street trees was cost effective in removing PM_{10}. The only exception was in the case of the medium socioeconomic stratum based on the low annual PM_{10} removal rates indicating that street tree management might not be cost effective in this socioeconomic stratum if the removal rate was at the lowest end of its expected range.

A variety of Chilean PM_{10} control devices measures and policies' based on studies conducted by Eskeland (1997), O'Ryan (1993) and the World Bank (1994) were compared against MUF management costs to determine if MUF management's cost efficiency was similar to these other air quality improvement measures and technologies (Fig. 2). MUF management costs in all of Santiago's socioeconomic strata were within the costs of these measures. Only the regulation of light duty gas vehicle emission standards had costs greater than the threshold value of 25 000 US$/ton/$PM_{10}$.

4. Discussion

The procedure developed for this analysis presents an innovative, simple, straightforward approach to examine the effectiveness of managing MUFs for air quality improvement within the confines of existing policies. The

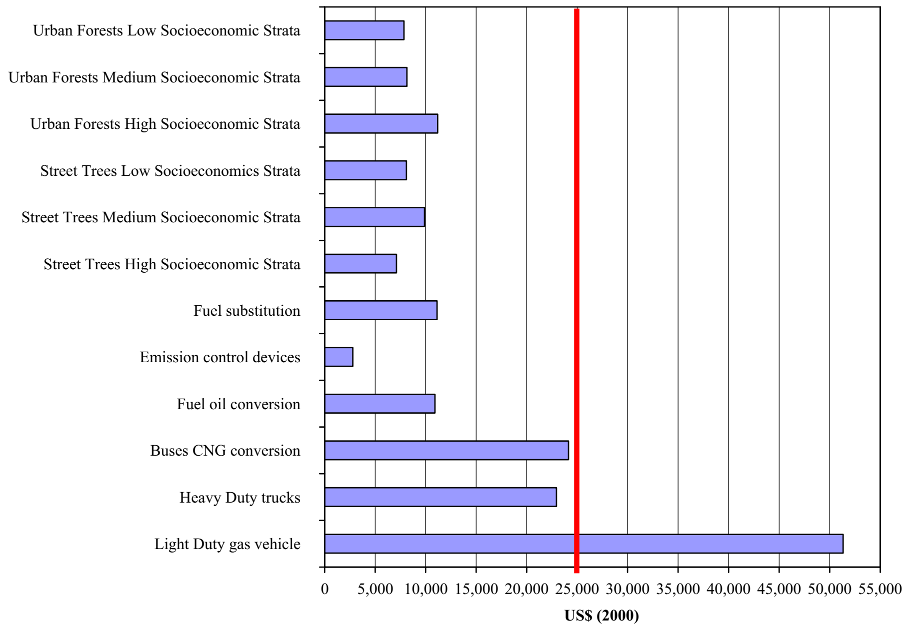

Fig. 2. Cost effectiveness of several PM_{10} abatement policies in Santiago, Chile. *Source*: World Bank (1994) and O'Ryan (1993). CNG, compressed natural gas; heavy duty trucks, regulation of heavy-duty truck emissions; light duty gas vehicles, regulation of light-duty vehicle emissions.

analysis indicates that managing MUFs and street trees are a cost-effective approach for abating PM_{10} in Santiago, Chile according to the PPDA. There are, however, two main caveats. First, the conclusions are based on UFORE estimates of MUF structure and annual PM_{10} removal rates (Tables 2, 3a, and 3b). The UFORE model has been used in previous studies to estimate urban tree and shrub effects on air quality (Nowak et al., 2002; Yang et al., 2005). However, the effect of grass on PM_{10} removal has not been well studied. Consequently, the PM_{10} removal rates and ranges for grasses, while based on the best available information, are more subjective than those for trees and shrubs. Even so, the estimated PM_{10} removal rates for MUFs are likely conservative as urban trees have other effects (e.g. reducing air temperatures, building energy use, and other air pollutants) not accounted for in this analysis. Second, the conclusions are based on the estimates of MUF management costs (Table 4). Given the nature of the cost data, the cost estimates probably overestimate the actual MUF management costs (Escobedo, 2004). Thus, the cost-effective estimates in Tables 5 and 6 are conservative. We have attempted to address both these issues by including a range analysis of both the removal rates and the cost data. Given these caveats, the conclusions of this study are tenable.

The results from this study indicate that in the case of Santiago, Chile urban forests are a cost-effective air quality improvement policy. That said, even if urban forests were not cost effective, urban trees can provide additional environmental benefits, for example, in their potential to sequester carbon and modify climate at no additional management costs (Escobedo, 2004). Urban vegetation also has additional environmental costs. Trees and shrubs can emit biogenic, volatile organic compounds (e.g. isoprenes, monoterpenes, and other organic compounds) that in combination with nitrogen oxides and under certain climate conditions, can contribute to ozone formation (Chameides et al., 1988). Urban vegetation also produces pollen which can aggravate allergies and emits carbon dioxide through maintenance activities and decomposition (Escobedo, 2004). Accounting for these additional environmental and economic benefits and costs was beyond the scope of this analysis.

5. Conclusion

Previous experiences from other parts of the world indicate that as low-cost options for air quality improvement are implemented, the costs of further reduction will increase (Hall, 1995; Maynard, 2001). Once these current technologies and policies have been implemented and exhausted, then the burden will fall on individual's behaviors and other more diffuse sources, thereby complicating air quality improvement programs (Krupnick and Portney, 1991).

As Chile integrates citizen participation in its environmental policies (e.g. the management of privately controlled urban forests), the opportunity presents itself for applying the pollution removal function of urban forests to encourage the political integration of its citizenry and local governments in the improvement of environmental quality. The metrics and methods from this study could provide *comunas* flexibility in satisfying environmental ordinances in a cost-effective manner. For example, one possible approach to incorporate urban forest cover within an air quality control program would be to develop a system of tradable permits based on each *comuna's* urban forest PM_{10} abatement potential (Main et al., 2000). Remote sensing protocols for determining urban forest cover could be used to enforce attainment of urban forest cover goals. Pollution removal rates for urban forests, as calculated by UFORE in this study, could be used to determine PM_{10} reduction effects. According to the World Bank (1994), sector arrangements could even be implemented to counteract the negative effects of urbanized *comunas* trading permits with that of peri-urban *comunas* and in doing so account for the discrepancy in pollution emission dynamics in urbanized central areas being treated as equivalent to pollution dynamics in outer non-urbanized areas.

Finally, many of the controversies involved with non-existent policies, valuation of benefits, time-dependent assumptions, and the complexities of atmospheric physics and chemistry and individual homeowner behavior were circumvented in this analysis. Variables and the methodology used were adjusted for the socioeconomic, environmental, and policy realities of a major Latin American city. Removal rates as quantified by UFORE were based on actual field measurements and real-time meteorological and pollution data. The procedure applied and the results from this study indicate that MUF and street tree management are cost effective in abating PM_{10} within the context of the PPDA and Chile's existing environmental and economic policies. It is hoped that this same procedure can be applied to examine the cost effectiveness of managing urban forest to improve air quality in other cities.

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