Chapter 7
Urban Air Pollution

Héctor Jorquera, Lupita D. Montoya, and Nestor Y. Rojas

Abstract Air pollution is currently the most serious environmental risk worldwide. Air pollution is the result of different driving forces (demography, economic growth, consumption patterns, energy options, cultural traditions, etc.) constrained by climate conditions, urban shapes and development patterns, distance to industrial or mining activities, air quality regulations and plans, etc. Air quality has been improving in some of the largest cities in Latin America, yet in most of them ambient air quality standards are not attained. In Brazil, Chile, Ecuador, and Mexico, the most polluted city is not the country's capital, emphasizing the relevance of sustainable local governance. In countries that report air quality just for their capital cities, most of their pollution levels are above the respective national ambient air quality standards. There is less information for mid-sized cities, and the available results are mixed. We present case studies from several countries that show serious air quality exposure for millions of inhabitants, especially the low-income segment. We discuss environmental justice, urban governance, and citizen participation in decision-making processes, sustainable urban transport options, and gender issues throughout those case studies.

Keywords Air pollution · Health impacts · Receptor modeling · Air quality management · Environmental justice · Sustainable urban development

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7.1 Introduction

The World Health Organization (WHO) estimates that, in 2014, as much as 92% of the world population was living in places where the WHO air quality guidelines levels were not met. Furthermore, around three billion people cook and heat their homes using open fires and simple stoves burning biomass (wood, animal dung, and crop waste) and coal. The WHO has estimated that in 2012 ambient and indoor air pollution caused 6.5 million premature deaths, an 11.6% of total global deaths; thus, it is the largest single environmental risk that society faces (WHO 2016a).

We present in Fig. 7.1 a conceptual framework (United Nations Environment Program [UNEP] 2016) to understand the linkages of air pollution with society. First, drivers such as population and economic growth produce pressures on the environment (increases in motor vehicles and fuel consumption, etc.) that constitute

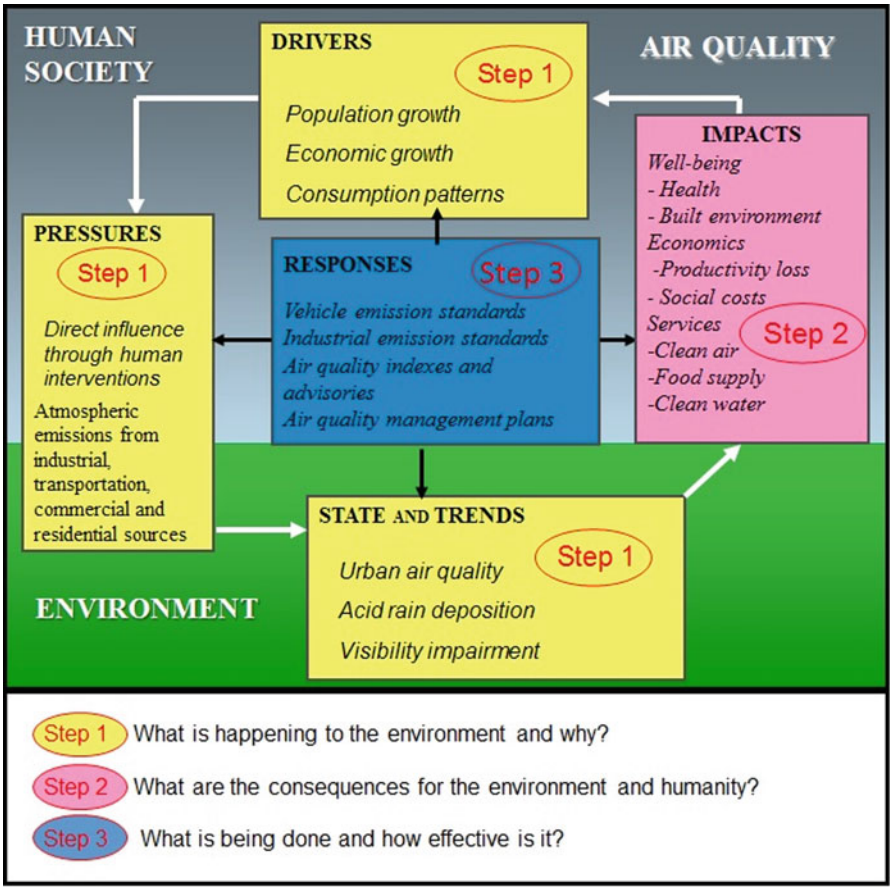

Fig. 7.1 The Driver Pressure State Impact Response (DPSIR) conceptual framework of the United Nations Environment Program (UNEP) (2016)

emissions of pollutants into the atmosphere by transport, industrial, commercial, and residential sources (Step 1).

Then, local and regional features (topography, meteorology, land uses) control the fate (state and trends) of those emissions, that is, ambient concentrations of air pollutants, deposition of dust and gaseous species (including acid rain), and visibility impairment (Step 1). This state of the atmosphere then determines the impacts on human health, ecosystem services, and the built environment, usually expressed in terms of social and economic damage (Step 2). Society's response to this problem comes in the form of policies oriented toward improving air quality; these policies may include the promotion of energy efficiency, sustainable urban transport, stricter emission standards for industrial, mobile, and residential sources, etc. (Step 3). The overarching goal is to maximize society's wellbeing, subject to natural, socioeconomic, and technological constraints.

In the following sections, we present the current state of air quality in Latin American cities and the major sources of ambient air pollution therein. Then we discuss three case studies: air quality management in Colombia, wood burning pollution in southern Chile, and indoor air pollution in Latin America. We summarize the major results in a conclusions and recommendations section.

7.2 State of Air Quality in Latin America

The first step in the conceptual framework laid out in Fig. 7.1 is to measure air quality. Historically, Latin American countries started air quality monitoring programs in the 1980s as a response to clear indications of high levels of air pollution in the major cities and industrial zones of several countries (Romieu et al. 1991). Currently, most Latin American countries monitor urban air quality to assess the state and trends of air pollution, to estimate population exposure and health impacts, and to evaluate the cost-effectiveness of regulatory measures.

According to the WHO's Global Urban Ambient Air Pollution Database (WHO 2016b) there are 122 cities in 16 Latin American countries that routinely report ambient concentrations of particulate matter $(PM)_{10}$ and $PM_{2.5}$, PM with an aerodynamic diameter below 10 and 2.5 μm respectively. We show a summary of those data in Table 7.1 below. Nine countries only report air quality in their capital city, and only six countries report seven or more cities.

Most of the cities with better air quality (i.e., annual PM_{10} below 30 μg/m^3) correspond to mid-sized cities (population less than one million inhabitants) or coastal cities with good ventilation conditions – such as Buenos Aires and Montevideo. The exception is Curitiba (Brazil), long known for its pioneering urban planning and sustainable urban transport. The picture for the most polluted cities (i.e., annual PM_{10} above 50 μg/m^3) is more complex and includes large cities (Santiago, Lima, Bogota, Mexico City) and mid-sized cities throughout South and Central America as well. In some of the largest cities (Mexico City, Sao Paulo, and Santiago), significant improvements in ambient PM_{10} and $PM_{2.5}$ concentrations

Table 7.1 Available annual ambient air pollution data for Latin American cities

Country (# cities)	PM_{10} summary, μg/m^3				$PM_{2.5}$ summary, μg/m^3			
Argentina/Buenos Aires			26				14	
Bolivia (2)	60	82	71	15.6	32	44	38	8.5
Brazil (45)	12	95	34	14.0	5	44	15	6
Chile (23)	12	75	46	15.5	5	64	24	12
Colombia (18)	18	52	40	9.7	9	41	20	7
Costa Rica (7)	20	47	29	8.7	14	30	22	6
Ecuador (9)	18	69	36	18.8	9	33	17	10
El Salvador/San Salvador			77				41	
Guatemala/Guatemala City			56				41	
Honduras/Tegucigalpa			59				36	
Mexico (9)	32	86	56	17.7	19	36	26	6
Panama/Panama City			31				14	
Paraguay/Asuncion			34				18	
Peru/Lima			88				48	
Uruguay/Montevideo			26				8	
Venezuela/Caracas			47				25	

WHO (2016b)
When four entries appear, they correspond to minimum, maximum, mean, and standard deviation of urban annual data for a given country

have been achieved since 1990. Hence, those cities' urban transport systems have reached more sustainable pathways.

The availability of ambient $PM_{2.5}$ concentrations is lower than for PM_{10}. In fact, most of the data compiled by the WHO (2016b) are estimates based on PM_{10} measurements, which means that ambient $PM_{2.5}$ is less frequently measured throughout the region. One way of estimating the spatial distribution of ambient $PM_{2.5}$ is to use satellite information. Several satellite missions orbit the Earth and provide estimates of the aerosol optical depth (AOD), a quantitative measure of how atmospheric particles attenuate light throughout the atmospheric column. Van Donkelaar et al. (2016) have collected available satellite information for AOD and combined it with ambient monitoring data and a global circulation model to obtain a global estimation of ground level $PM_{2.5}$. Fig. 7.2 shows their results for the Latin American region in 2015; the estimated spatial variation shows higher values at large metropolitan areas and desert regions, low values at coastal regions and remote zones (such as Patagonia). However, it should be remembered that those estimates involve uncertainties brought about by the estimation process.

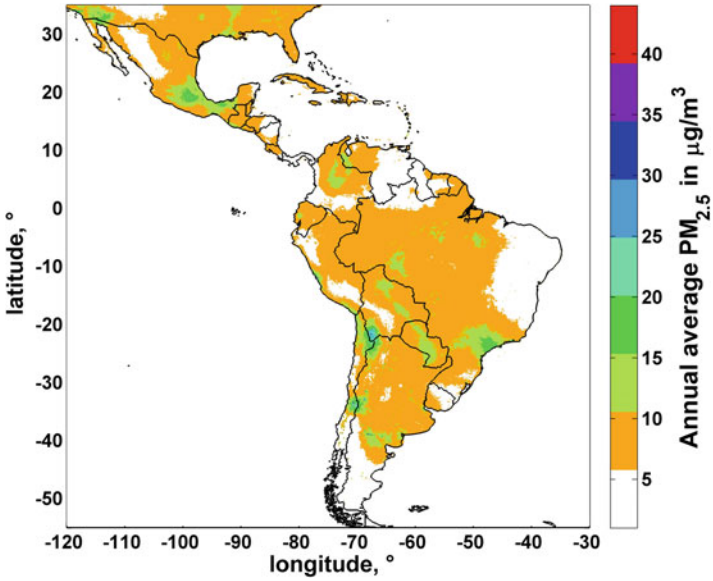

Fig. 7.2 Spatial distribution of ground level $PM_{2.5}$ ($\mu g/m^3$) in Latin America. (Data downloaded from: http://fizz.phys.dal.ca/~atmos/martin/?page_id=140. Accessed: November 2016)

7.3 Where Does Air Pollution Come From?

This question usually arises once air pollution has been measured. Answering this question requires obtaining a list of air pollution sources (traffic, industry, commercial, residential, natural) and the amount of air pollution that each of them contributes to the total burden at a given city; in this way, all relevant sources can be ranked according to their contributions. Following the conceptual framework depicted in Fig. 7.1, that answer completes step 1, identifying the sources to be regulated in step 3. Likewise, knowing how source contributions change with time allows for assessing how effective current air quality initiatives are; this also contributes to step 3 in the framework of Fig. 7.1.

There are two different methods of estimating the contribution of air pollution sources to air quality: dispersion models and receptor models. Dispersion models, also known as chemical transport models, simulate the meteorology in a given area (urban, regional, continental or global) and how the atmospheric emissions (coming from natural, residential, commercial, industrial, and transport sectors) are transported and physically and chemically processed in the atmosphere (Seinfeld and Pandis 2006). The result is a prediction of the spatial and temporal distribution of pollutants over a city or region, and estimates of how much each sector contributes to the air quality therein. However, this approach requires spatially (~ 1 km) and temporally (~ 1 h) resolved atmospheric emissions inventories, which in turn require substantial resources to be compiled. Because of that, few dispersion model results

have been published for Latin American cities, especially those that predict source contributions to air pollution concentrations.

7.3.1 Receptor Models

Receptor models are statistical models that identify and quantify the sources of ambient air pollution and their effects at a site (receptor), using concentration measurements at a receptor site without using emission inventories or meteorological data (Belis et al. 2013; Hopke 2016). Therefore, receptor models are independent of and complementary to the above-described dispersion models.

The approach to obtaining a data set for receptor modeling is to determine a large number of chemical constituents such as elemental concentrations in a number of ambient PM samples. As some chemical species (denoted as tracers or markers) are only emitted by one (or a few) sources, a solution can be obtained, provided we include enough tracers/markers to constrain the solution sought. Any solution corresponds to a minimization of the differences between ambient data X and model data, which can be expressed as a mass balance equation:

$$X_{ij} = \sum_{k=1}^{p} g_{ik} f_{kj} + e_{ij} \tag{7.1}$$

where X_{ij} is the j-th species mass measured at the i-th sample, g_{ik} is the PM mass concentration from the k-th source contributing to the i-th sample, f_{kj} is the j-th species mass fraction from the k-th source, and p is the total number of independent sources (Hopke 2016). Finally, e_{ij} is an uncertainty term introduced to facilitate a statistical solution of the mass balance as opposed to an analytical mathematical solution to Eq. (7.1).

The number of sources (p) that can be resolved from Eq. (7.1) is highly dependent on the number of samples (n) and the properties of the m species considered above. The two most commonly used methods of solving the above equation are (Hopke 2016):

1. In the chemical mass balance (CMB) approach, the F matrices are known source profiles; thus, a system of linear equations is solved on a sample-by-sample basis using effective variance least squares, which is the basis of the United States Environmental Protection Agency's CMB model (US EPA 2016a). Here, the number m of chosen tracer species should be equal to or greater than the number of factors sought.
2. The F matrices are unknown, so they are iteratively estimated; thus, they are denoted as factor profiles. The most frequently used receptor model of this kind is Positive Matrix Factorization (PMF), which minimizes the following objective function (US EPA 2016b):

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} \left[\left(X_{ij} - \sum_{k=1}^{p} g_{ik} f_{kj} \right) / \sigma_{ij} \right]^2 \tag{7.2}$$

where σ_{ij} is the estimated uncertainty in the j-th species at the i-th PM sample. There are two main assumptions for the mass balance in the above methods:

1. That source profiles do not change significantly over time or do so in a reproducible manner so that the system is quasi-stationary for CMB depends on them not changing.
2. That receptor species do not react chemically or undergo phase partitioning (solid/gas or solid/liquid) during transport from source to receptor (i.e., they add linearly). Metals are excellent receptor species with respect to assumption 2 and they have been used from the very beginning of receptor modeling. They are truly "tracers" because they preserve their identity as they are transported from a source to a given site (receptor). As the measurement of chemical source profiles is expensive and requires significant experimental facilities to conduct the tests, most of the reported studies from Latin America have been carried out using the PMF framework or similar techniques; the number of published applications of CMB is smaller. Once the source apportionment solution is generated, the contributions of each source are estimated, on a daily basis, by using the following multiple linear regression:

$$\mathrm{PM}_i = \sum_{k=1}^{p} \beta_k g_{ik} + e_i \tag{7.3}$$

where PM_i is the daily concentration of PM (PM_{10}, $\mathrm{PM}_{2.5}$, etc.) on day "i," g_{ik} are the source contributions (normalized, so that their average is 1 for each source k), e_i is an uncertainty term on day "i" and β_k is the average contribution of source "k" to ambient concentrations of PM. It is a customary assumption that all major PM sources have been identified (except perhaps biological sources and secondary aerosols); thus, the above regression coefficients $\{\beta_k\}$ should be positive and statistically significant (for instance, its p value <0.05). A negative value in $\{\beta_k\}$ means that too many sources are included in the receptor model; therefore, the receptor model should be run again with *p-1* sources, etc.

7.3.2 Source Apportionment Results in Latin American Cities

We summarize here the results published by Karagulian et al. (2015), who compiled available source apportionment studies worldwide and classified the identified sources as sea salt, dust, traffic, industry, biomass/residues burning, and other anthropogenic sources. This uniform source classification allows for meaningful

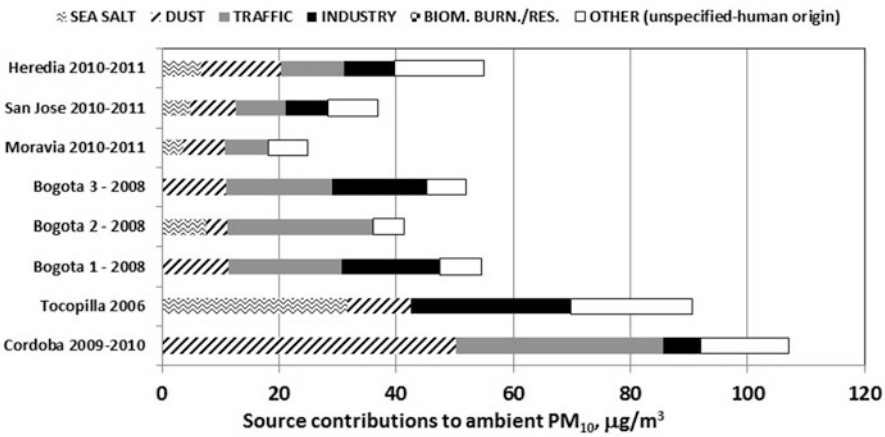

Fig. 7.3 Summary of source apportionment results for ambient PM_{10} in Latin American cities. (Source: WHO (2016a, b, c))

comparisons among countries, cities, and study years. The database released by the WHO (2016c) includes studies published up to 2014, and we have added one study published for Santiago (Villalobos et al. 2015).

Figure 7.3 shows the results for ambient PM_{10} concentrations. Almost all cities exceed the annual value of 25 μg/m^3, the WHO recommended guideline (WHO 2005). Sea salt (marine aerosol) is relevant at coastal cities such as Tocopilla (Chile) and the three Costa Rican cities at the top of Fig. 7.3. Traffic is greater in the larger cities (Bogota, Colombia, and Cordoba, Argentina). Dust is present in all cities, usually as a mixture of surface soil suspended by wind (natural contribution) and urban dust, the result of road dust abrasion and resuspension by traffic. Industrial contributions are highest at Tocopilla, a port city with several coal-fired power plants, and lowest at Moravia, Costa Rica, a small city away from major industrial activities. The biomass/residue burning contribution is not present, although it may be included within the "Other" classification. At Bogota, three sites were analyzed in 2008, two of them are residential sites and one is an industrial part of the city; it is clear from the Fig. 7.3 that only one of the residential sites is far enough from industrial sources. This shows that source receptor analyses may diagnose environmental justice issues.

Figure 7.4 shows source apportionment results for ambient $PM_{2.5}$ concentrations. For ease of visualization, we prioritize studies at the same city in different years instead of showing all results. None of the cities meets the WHO guideline of 10 μg/m^3, as a long-term average (WHO 2005). Coastal cities (Rio de Janeiro and Recife in Brazil) have better air quality than continental cities in valleys surrounded by mountains (Cordoba, Mexico City, Santiago). In Rio de Janeiro, Sao Paulo, and Santiago, ambient $PM_{2.5}$ has increased, with traffic sources on the rise, but industrial contributions decreasing. The first trend may be a result of an increase in motor vehicles (ECLAC 2016), whereas the second trend may be due to more regulations

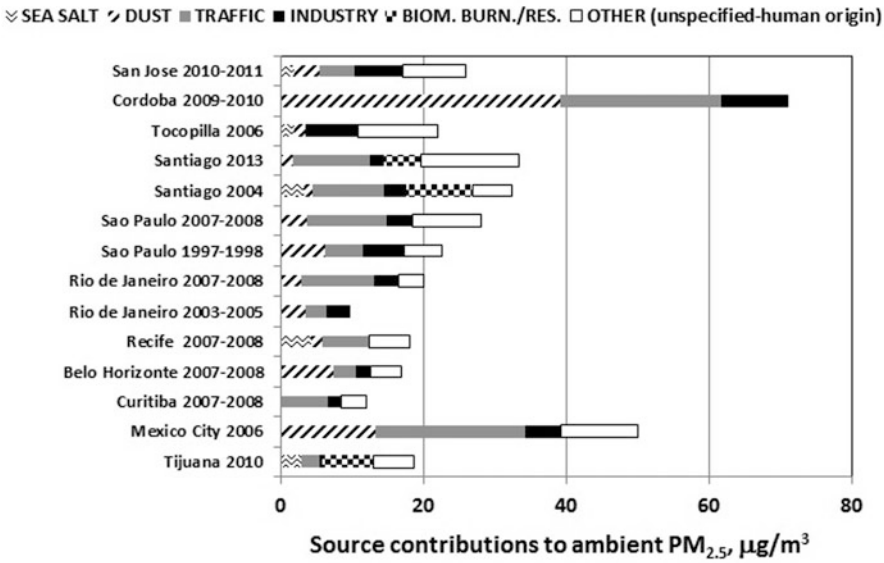

Fig. 7.4 Summary of source apportionment results for ambient $PM_{2.5}$ in Latin American cities. (Source: WHO 2016a, b, c)

upon industry. Owing to climate conditions, wood burning is only relevant at Santiago and Tijuana, Mexico; the trend at Santiago is downward.

7.4 Air Pollution Monitoring and Management in Colombia

7.4.1 Introduction

In January and early February 2016, unusually dry conditions over Bogota – the capital and largest city of Colombia with nearly eight million inhabitants – associated with a long El Niño period, caused strong thermal inversions and a critically stable atmosphere. Dust resuspension increased because of a soil that was drier than usual. Because of drier vegetation, forest fires started in the region and on the mountains along the Eastern border of the city. For more than 3 weeks, as a result, airborne PM concentrations reached alarmingly high values (82 $\mu g/m^3$; AQI = 165), considered unhealthy for sensitive groups or unhealthy according to the air quality index scale (SDA 2016). On 1 February, the strongest and closest forest fires produced emissions that infused the city with heavy smoke, causing several institutions at the historical town of La Candelaria and its surroundings to be evacuated. On 4 February, the city celebrated one of its two annual car-free days. The event promoted sustainable urban transportation by reducing light-vehicle emissions significantly, but slightly increased PM emissions from its diesel-powered bus-only

transit system because more buses were in service. Many citizens used their bicycles to go to work, but unfortunately, they exposed themselves to air that was much more polluted than usual. Although local health and environmental agencies declared an orange alert, communications to the public through social media were scarce and unclear about the risk that such high PM concentrations posed to people's health. The authorities issued no special communication to bicycle users or pedestrians regarding air pollution and how to use respiratory protection on the car-free day.

One month later, still under the effect of the dry conditions of El Niño and the incidence of forest fires on the North of Colombia, strong atmospheric stability conditions occurred at the Aburra Valley, where Medellin – Colombia's second largest Metropolitan Area – home of nearly 3.5 million inhabitants, is located. Between 5 March and 3 April, $PM_{2.5}$ concentration levels were deemed unhealthy for sensitive population groups, with an average of 68 μg/m^3 – AQI = 157 and a maximum daily average of 103 μg/m^3 – AQI = 176 (Universidad Nacional de Colombia 2016). The episode was unusually severe and long, and triggered a determined, though late, response from the Mayor of Medellin and his government collaborators. On 18 March, a set of risk communications was issued to the public and emission reduction measures were taken, focusing on diesel-powered trucks and buses, in addition to motorcycles and scooters. Authorities ran an air quality model to evaluate mitigation measures and decided to celebrate two car-free days on 2 and 3 April, promoted working from home, and invited private companies to join the government in their efforts to reduce emissions. In addition, emergency response protocols were revised.

These two episodes are examples of the many contrasts found in Colombia's air quality management. In these examples, both cities have strong air quality monitoring networks, but responses from the authorities to high air pollution episodes were utterly dissimilar, despite the existence of a set of National Air Quality Policies that includes air quality standards and emission regulations, in addition to air quality monitoring and emission testing protocols. Differences are even stronger when other cities and smaller towns are considered. This is because of the way in which the national environmental system is designed. Decisions about the number and type of monitoring stations, in addition to enforcement strategies, are taken autonomously by regional or city-level agencies, following a nonbinding set of air quality monitoring and management guidelines, according to their own budget and technical capacity.

Of the 20 largest cities in Colombia, 16 have at least one air quality monitoring station (IDEAM 2016). However, nearly 40% of people living in urban areas in Colombia are not covered by the ambient air quality monitoring network. In addition, existing systems are highly heterogeneous. Costly automatic stations are used in large urban areas such as Bogota, Medellin, Cali, and Bucaramanga, and some towns with important high-emission activities such as mining and brick production. Other cities and towns rely on inexpensive, manual stations that do not provide continuous information. Most of the ambient air quality monitoring stations in Colombia (88%) focus primarily on PM_{10} monitoring. $PM_{2.5}$ and gaseous pollutants are measured at only ~20% of the stations, mostly in the largest cities;

however, the number of $PM_{2.5}$ monitors is increasing, given its significant impact on human health. Measurement quality is also a concern with the existing air quality monitoring systems. Around 23% of the installed monitoring capacity does not produce data that can be considered of high quality, defined as providing at least 75% valid measurements (IDEAM 2016). This is associated with deficiencies in structural capacity, such as the number or performance of personnel in charge of air quality monitoring, and the operation and maintenance of the monitoring technology.

The highest PM_{10} concentrations, consistently exceeding the annual-average Colombian Air Quality Standard of 50 μg/m^3, occur in the following areas:

1. The southwestern area of Bogota
2. The Cesar open-pit coal mining-influenced area
3. Small towns influenced by brick kiln production
4. The southern part of the Aburra Valley – Medellin Metropolitan Area. These areas are, roughly, the same as those that show consistent exceedances of the $PM_{2.5}$ Colombian Ambient Air Quality Standards (25 μg/m^3 as the annual average and 50 μg/m^3 as the 24-h average).

The southwestern area of Bogota has the highest number of the PM_{10} 24-h average exceedances, reaching 100 in 2015. It is a highly populated area, with a density of 25,000/km^2. Therefore, it constitutes the highest public health concern related to air pollution in Colombia.

7.4.2 Bogota, An Unfinished Success Story

Air quality records at Bogota show that the most concerning pollutant is PM (IDEAM 2016; Secretaria Distrital de Ambiente [SDA] et al. 2010). Figure 7.5 shows that PM_{10} concentration levels increased from ~50 μg/m^3 in 1998 to 75 μg/m^3 in 2005 and were reduced after 2007, to levels around or below 50 μg/m^3 after 2012 (Observatorio Ambiental de Bogota 2016), which can be considered successful for an economy that was growing steadily during the same period. After 2014, however, PM_{10} concentrations seem to be leveling off. Ambient $PM_{2.5}$ monitoring started in late 2013, showing an annual average of 23 μg/m^3 in 2014 and 20 μg/m^3 in 2015, about twice the WHO guideline (WHO 2005).

Concentrations of PM_{10} and $PM_{2.5}$ are highly heterogeneous across the city. Figure 7.6 shows (a) PM_{10} and (b) $PM_{2.5}$ monthly averages between January 2014 and April 2106 for the following four areas of the city: north east, east–south east, north west, and west–south west, each one grouping a subset of air quality monitoring stations (shown in Fig. 7.7). It is evident that there is a strong west–east difference, between 17 and 39 μg/m^3 during this period. This difference is explained by the high concentration of industrial sources in the western and south western areas. There is a significant number of small and medium-sized industrial manufacturing facilities, many of which use coal or fuel oil and are not equipped

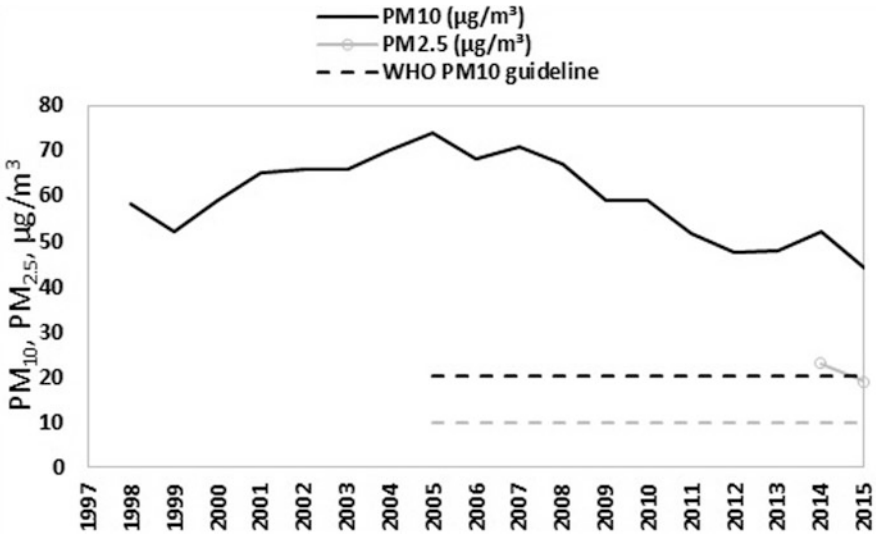

Fig. 7.5 Ambient PM_{10} and $PM_{2.5}$ annual averages at Bogota (IDEAM 2016)

with efficient emission controls. These include the country's largest food distribution center – Corabastos. There are highly congested roads with high flow rates of heavy-, medium- and light-duty diesel trucks associated with the previous facilities, in addition to high flow rates of diesel-powered transit buses and gasoline vehicles. Low-income, high-density housing is mixed with industrial facilities. The zone also has high rates of dust resuspension (Carmona-Aparicio et al. 2016; Perez-Peña et al. 2017). Figure 7.8 emphasizes the above by showing the spatial distribution of PM emissions rates from point and mobile sources on a 1-km × 1-km grid during 1 h at 12 m on a typical working day on 2012 (Rojas and Peñaloza 2012). Another factor is meteorology, with higher wind speeds on the eastern area that contribute to a better dispersion of pollutants, and lower on the western area, contributing to pollutant accumulation. In addition, records show lower precipitation rates and, hence, drier soil in the western than in the eastern area, reducing wet deposition and promoting more dust resuspension.

Still, emission inventories and source apportionment studies have not been conclusive about the contribution of different sources to PM in the city and the influence of aerosols transported from other regions of Colombia. Table 7.2 shows that there are significant differences among source apportionment studies conducted during different periods. These differences are likely the result of different sets of chemical components included in the PM speciation and different mathematical techniques used to find the contributing factors – see Sect. 7.3.1. From these, the most complete set of species was analyzed by Vargas et al. (2012), who found that mobile sources accounted for between 35% and 60% of PM_{10}; industrial sources, between 18% and 44%; dust resuspension, between 9% and 21%; and secondary

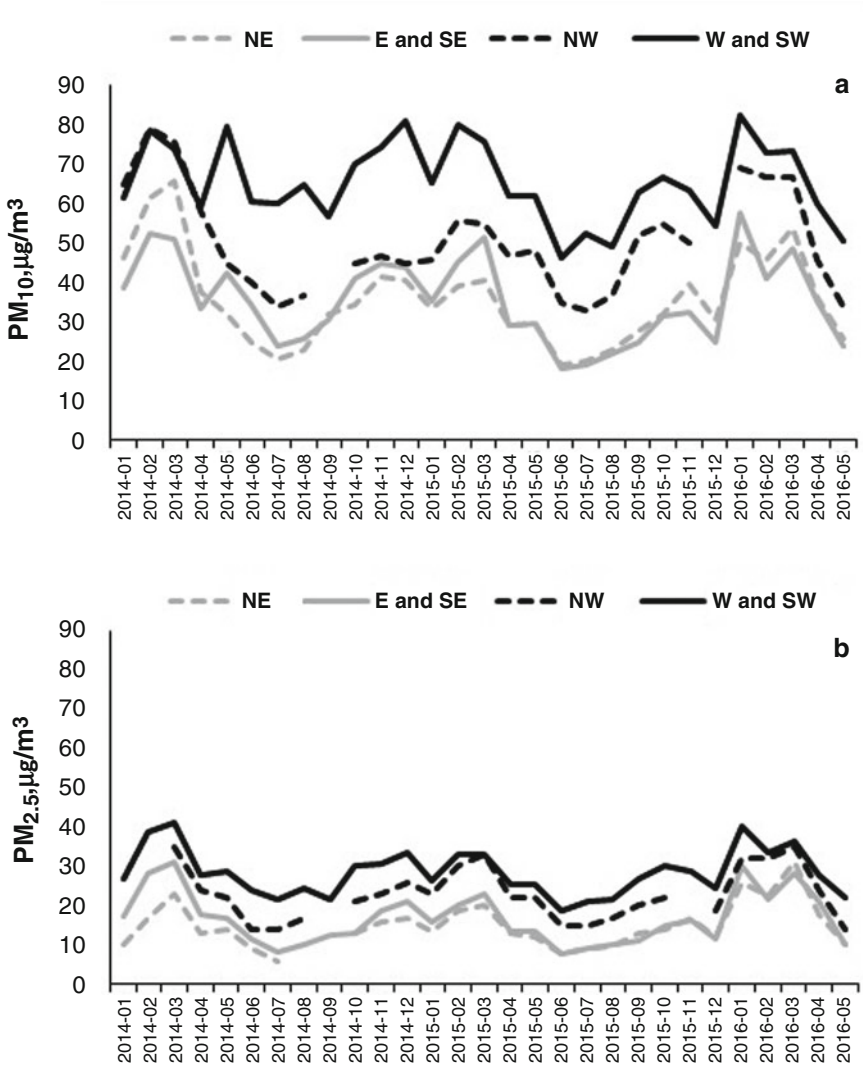

Fig. 7.6 PM_{10} (**a**) and $PM_{2.5}$ (**b**) monthly averages in four areas of Bogota since 2014. (IDEAM 2016)

aerosol, 13%. Clearly, the city government should prioritize emission controls for mobile sources throughout the city, particularly diesel buses and trucks, and strengthen industrial emission controls at the industrial south western area. Street sweeping with vacuum cleaning devices could also be implemented to reduce dust resuspension, especially in the south western area, during dry seasons.

A set of emission controls were established for the city's 2010–2020 Air Pollution Abatement Plan (Secretaria Distrital de Ambiente [SDA] et al. 2010), with the

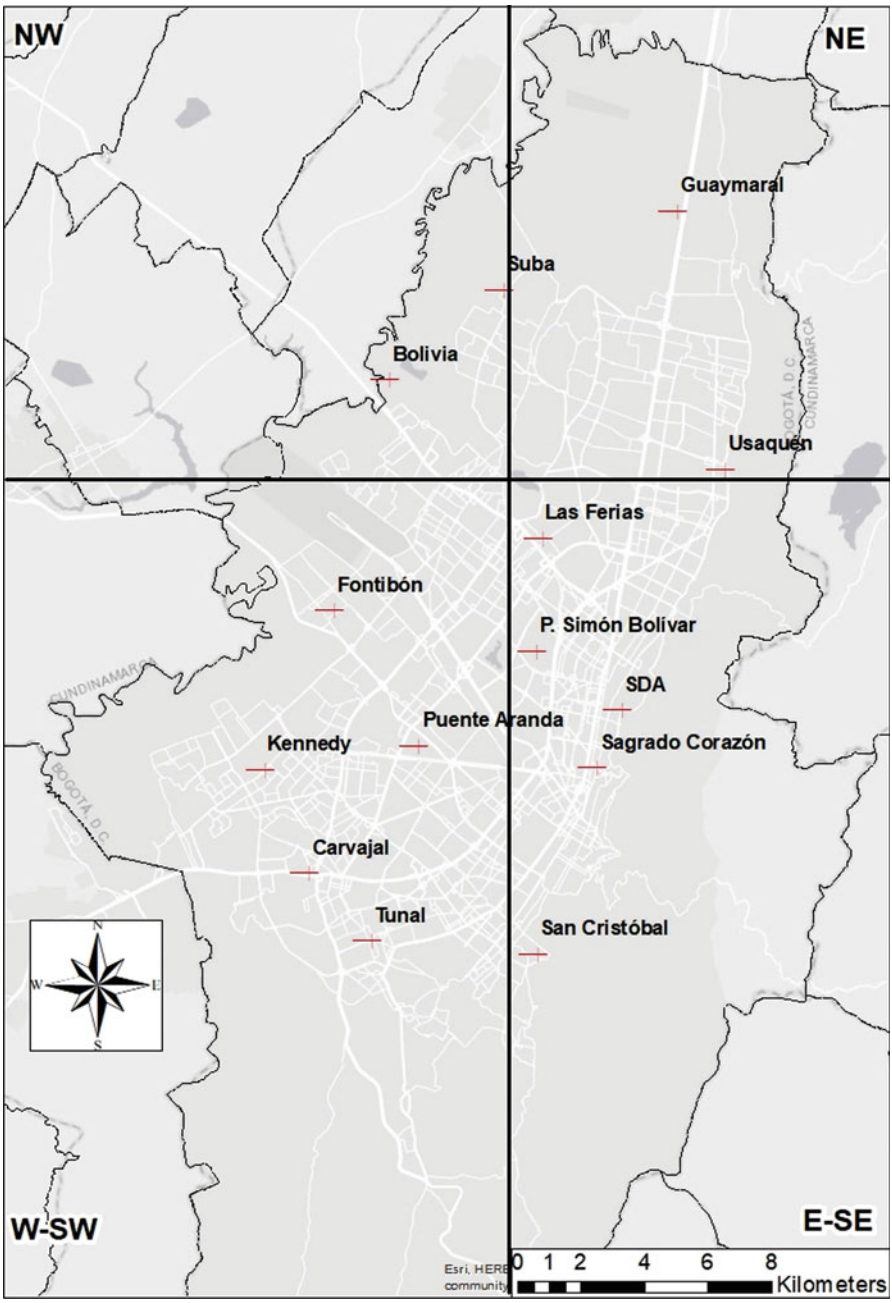

Fig. 7.7 Location of Bogota's air quality monitoring stations

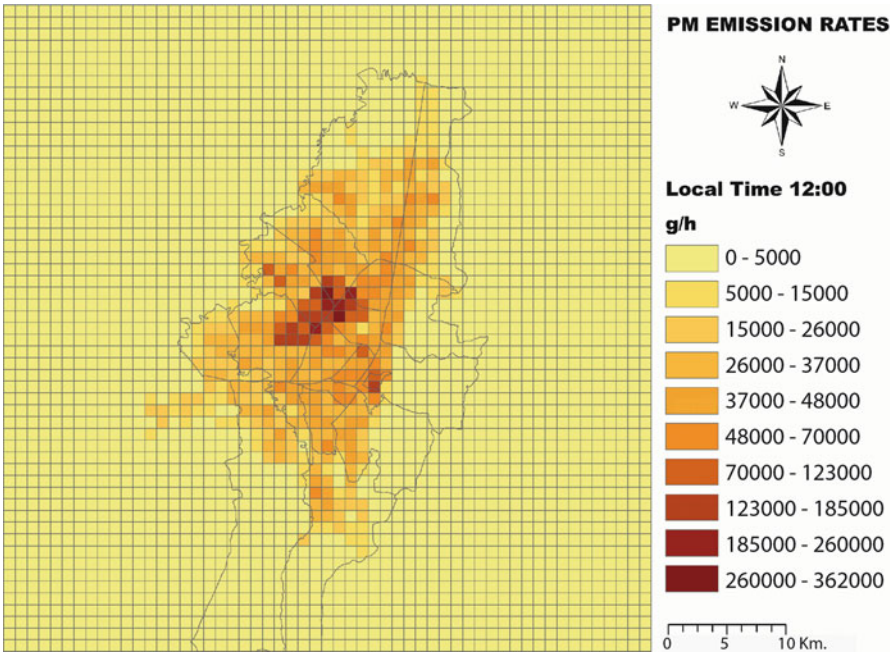

Fig. 7.8 Spatial disaggregation of PM emission rates in Bogota at 12:00 on a working day. (Rojas and Peñaloza 2012)

goal of meeting the ambient PM_{10} annual average national air quality standard in every monitoring station, and reduce significantly the number of exceedances of the 24-h standard by 2020. Health benefits associated with this plan were estimated to be around seven billion dollars over 10 years, from avoided premature deaths and avoided morbidity (Ortiz-Durán and Rojas-Roa 2013). The most important measures included reorganizing the public transit system and installing Diesel Particulate Filters (DPFs) in diesel buses and trucks, in addition to PM emission control devices for industrial facilities. Major changes upon the public transit system – performed between 2012 and 2015 – and diesel fuel with a sulfur content lower than 50 ppm – available since 2010 – can explain the observed reduction of PM_{10} throughout the city. Installing DPF systems has not yet been possible, despite significant efforts by the environmental agency; thus, black smoke puffs from diesel buses and trucks, even new ones, are frequent street sights. With a rapidly growing number of light vehicles and motorcycles, and the associated increasing congestion, further reductions in PM_{10} and $PM_{2.5}$ concentration levels are not foreseeable during the rest of the Plan's implementation period.

Table 7.2 Source contribution to PM_{10} estimated from receptor modeling studies in Bogota

	Residential site		Industry influenced site		Traffic influenced site
Source	Behrentz et al. (2009)	Vargas et al. (2012)	Behrentz et al. (2009)	Vargas et al. (2012)	Behrentz et al. (2009)
Resuspended dust	60%	9%	42%	21%	52%
Mobile sources	3%	60%	0.7%	35%	29%
Industrial sources	17%		23%		9%
Non-ferrous foundries				10%	
Nitrate-rich source				21%	
Sulfate-rich source				13%	
Ion-rich source		18%			
Secondary aerosol		13%			
Unidentified source	20%		34%		10%

Adapted from Vargas et al. (2012), Secretaria Distrital de Ambiente (SDA) et al. (2010)

7.5 Wood Burning Pollution in Southern Chile

Wood burning pollution is a severe problem in Southern Chile (beneath 35° S). Two million people living in Southern Chilean cities are exposed to annual $PM_{2.5}$ concentrations above 30 μg/m^3 (MMA 2014). This high air pollution comes from a widespread use of wood for space heating and cooking – it is the cheapest fuel available. Furthermore, most people burn wood using inefficient stoves in households with poor thermal insulation (Schueftan and Gonzalez 2015) and they often choke the air inlet so that combustion slows down and PM emissions rise (Jordan and Seen 2005; Tissari et al. 2008).

Figure 7.9 shows annual ambient $PM_{2.5}$ measured at several cities in Chile through the National System of Air Quality Information (MMA 2016); $PM_{2.5}$ urban ambient concentration (averages for 2013–2015) are plotted against the heating degree days (HDDs, a proxy for household heating demand). The almost linear relationship for the southern cities (HDD > 1100 °C-days) suggests that wood burning emissions dominate ambient $PM_{2.5}$ concentrations there. Figure 7.10 shows that ambient $PM_{2.5}$ concentrations rise in the evening and peak near midnight; thus, those emissions cannot come from mobile sources.

The problem originates from a combination of several factors. First, southern regions have the highest rates of poverty in Chile; this means a large fraction of the

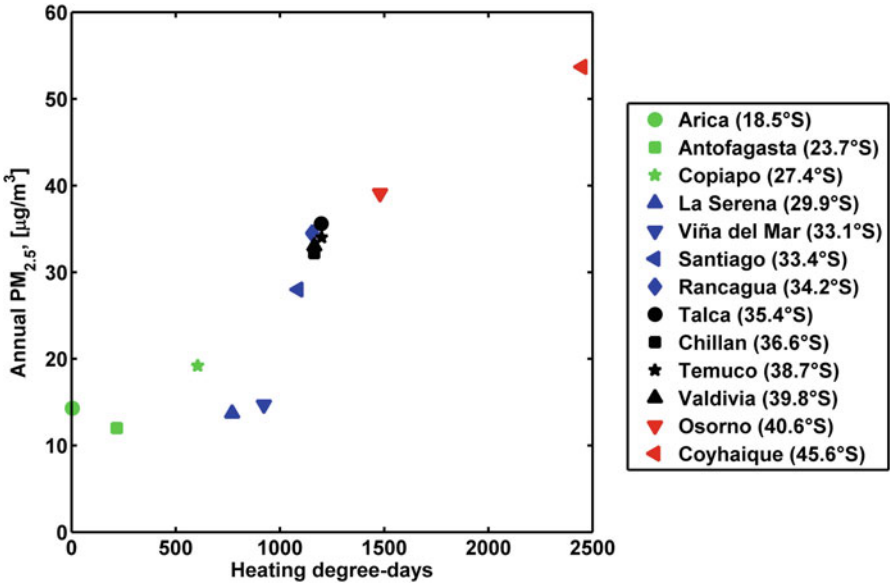

Fig. 7.9 Annual ambient $PM_{2.5}$ (average for 2013–2015) at selected Chilean cities plotted against heating degree days (HDDs) in °C/day. (HDDs retrieved from www.degreedays.net)

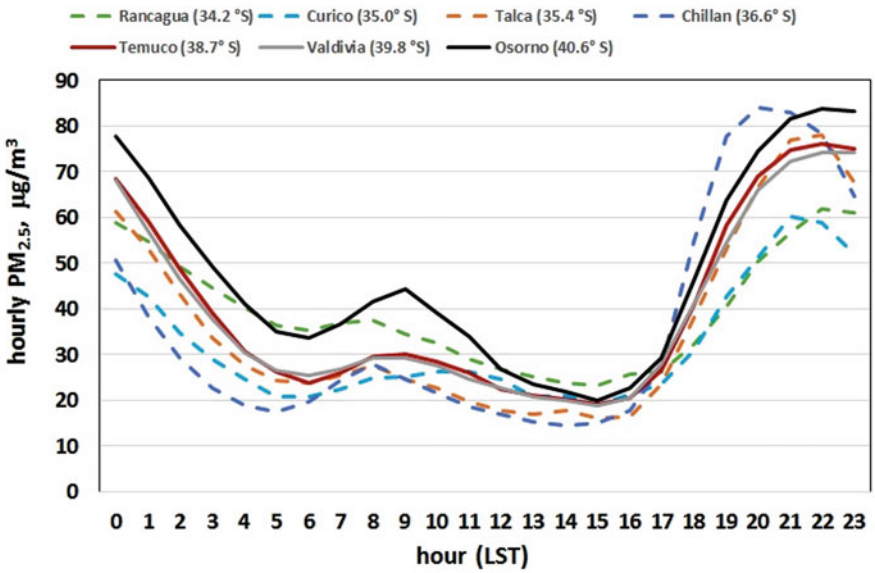

Fig. 7.10 Hourly profile of ambient $PM_{2.5}$ in several Chilean cities, during the austral cold season (May–August). (Source: MMA (2016))

population only has access to subsidized, low-quality housing. Second, a large fraction (85%) of households were built before 2007; thus, they lack adequate thermal insulation and are leaky (Schueftan and Gonzalez 2015), increasing household heating energy demand. Third, the cultural preference for burning wood (Reeve et al. 2013) and the fact that it is the cheapest fuel available make most households use it, even for cooking. Fourth, there is a large stock of old, inefficient wood stoves and cook stoves; most households operate stoves under air-choked burning conditions, when emissions are highest. Fifth, the wood market is largely informal and the wood sold has high moisture contents, which promote high emissions on any wood stove. A better option is to purchase dry wood in summer to stock up for the cold season, but people on low incomes cannot afford that. In summary, cultural, socioeconomic, and technological factors combine to produce a complex scenario of severe air pollution.

The authorities have implemented several initiatives to curb pollution from wood burning. The long-term measures include:

1. Wood stove replacement program
2. Subsidies for household thermal refurbishments

Both are aimed at improving household energy efficiency, and the government also promotes biomass as a renewable fuel coming from well-managed forest resources. However, the scale of the problem described above means that air quality improvements will take years to be accomplished.

The government has also implemented a pioneering, short-term air quality regulation. It uses an air quality forecasting system that predicts air pollution conditions 1–3 days ahead (Saide et al. 2016). With this technological tool, authorities can enforce bans on wood burning in selected districts within each southern Chilean city. This short-term strategy has been effective in reducing the magnitude of air pollution episodes in the last 3 years. Given the complexity of the problem, that short-term strategy would need to be operative in the coming years as well.

7.6 Indoor Air Quality in Latin America

Indoor air pollution has been consistently identified as a leading cause of morbidity and mortality for the past 25 years. In 2010, air pollution accounted for two of the top three biggest factors in disability-adjusted years in the world for both genders. Increasing scientific evidence is uncovering the complex and extensive level of health effects that air pollution has on the human body. Historically, the highest levels of indoor air pollution have been registered in developing communities (DCs), where there is limited access to clean energy. Although there have been many attempts to solve the air pollution crisis throughout the world, these efforts have resulted in limited success.

There is scant information about the state of indoor air quality (IAQ) in Latin America. The emphasis so far has been on ambient air quality and advancing

Table 7.3 Smoke-free national policies in Latin America

Country	Year	Comments
Uruguay	2006	100% smoke-free national policy
Panama & Colombia	2008	100% smoke-free national policy
Guatemala	2009	Exceptions allowed for smoking in hotels
Peru	2010	100% smoke-free national policy
Honduras	2010	Exceptions allowed for smoking cubicles in cigar factories
Brazil	2011	100% smoke-free national policy
Venezuela	2011	100% smoke-free national policy (Ministerial Regulation)
Ecuador	2011	Exceptions allowed for smoking in hotels
Argentina	2011	Exceptions allowed for smoking in private enclosed workplaces
Costa Rica	2012	100% smoke-free national policy

ambient air regulations in the region. However, there have been a few cases where poor communities have been the subject of multiple studies, such as in rural Guatemala (e.g., Boy et al. 2000, 2002), Chile (e.g., Cortés and Ridley 2013; Sanhueza et al. 2006), and Mexico (Ramírez-Venegas et al. 2014; Regalado et al. 2006). There have been also a few IAQ studies conducted in urban settings (Barraza et al. 2014, 2016; Burgos et al. 2013).

7.6.1 Indoor Air Quality Regulations in Latin America

Indoor air quality regulations in Latin America have revolved primarily around enacting smoke-free policies after the adoption of the World Health Organization (WHO) Framework Convention on Tobacco Control (FCTC) in 2005 (Sebrié et al. 2012). The FCTC provided the mechanisms needed to enable national and subnational legislations to effectively protect people from second-hand smoke. Since then, several Latin American countries have enacted smoke-free policies in public places. Table 7.3 shows the list of countries that have adopted such policies. Some of these are 100% smoke-free policies at the national level, whereas others have included notable exceptions.

Some local smoke-free policies have been enacted in places like Mexico City (Thrasher et al. 2010). All these initiatives have been encountered by strong opposition from the tobacco industry, which has often turned to litigation to stop them.

7.6.2 Gender and Environmental Justice Issues

In general, the preponderance of the burden of indoor air pollution is faced by the poorest sectors in Latin American countries, often the rural and urban poor. The incidence of rural poverty has been consistently above 50% in many Latin American

countries (de Janvry and Sadoulet 2000), particularly when it is defined as multidimensional poverty (Battiston et al. 2009). Consequently, the burden of poor IAQ is shouldered by very large segments of these populations, due mostly to their limited access to clean energy and sustainable housing.

In poor communities, the use of solid fuels indoors is extensive. Depending on the country and region, the fuels can range from animal waste, as in the Andean region of Peru (Gomez et al. 2011) to wood in southern Chile (Cortés and Ridley 2013) and coal in rural Guatemala (Boy et al. 2002). The associated health effects due to indoor air pollution exposure in these communities have received some attention (Smith-Sivertsen et al. 2009), although much of what we know is deduced from studies conducted in developed countries at much lower pollution levels.

In these communities, exposure to indoor air pollution from solid fuel use disproportionally affects women. Because of strong gender role segregation, women are usually in direct contact with indoor combustion emissions during cooking and heating activities. Small children also become exposed as they are in the care of their mothers and often, for the poorest sectors, are attached to them.

In addition to the exposure to indoor air pollution from solid fuel use, cigarette smoke and secondhand smoke pose additional risks to poor communities and to poor women, in particular. The extent of this exposure and the corresponding health effects have not been properly evaluated in Latin America; however, Pichon-Riviere et al. (2016) determined that cigarette smoking is responsible for about 33.6 billion US dollars in direct costs to health systems in Latin America. A study on the prevalence of smoking in Brazil (Godoy 2010) also found that smoking decreased at much higher rates for men and women with higher purchasing power than for those with lower purchasing power (i.e., poorer population).

A study conducted in the USA (Klein et al. 2014) found that comprehensive smoke-free policies may improve preconception health among a population at risk for smoking and can be associated with a reduction in smoking among low-income women. Similar studies should be conducted in Latin America.

7.6.3 Case Studies in Indoor Air Quality

7.6.3.1 Argentina

In the case of Argentina, it is appropriate to focus on research related to secondhand tobacco smoke (SHS). Argentina was the first country in the region to adopt 100% smoke-free policies at the sub-national level starting in 2006, allowing comparisons among cities with differing policies. These smoke-free policies have been opposed by the tobacco and by the tourism industry.

As part of the Global SHS Research Study (Hyland et al. 2008), the levels of indoor air pollution in hospitality venues (bars, discos, pubs and restaurants) in 15 cities in Argentina were evaluated by Schoj et al. (2010). Among the 15 selected

cities, there were 5 smoke-free cities, 3 with partial smoking restrictions, 3 with no legislation, and 4 in transition to 100% smoke-free legislation.

The results of this study showed that the levels of $PM_{2.5}$ in cities with no legislation were five times higher than those in smoke-free cities. For cities in transition to smoke-free legislation, the levels of $PM_{2.5}$ decreased significantly after enacting the policies. Similarly, for cities with designated smoking areas (partial smoking restrictions), $PM_{2.5}$ levels were not statistically different between the smoking and nonsmoking areas. Overall, this study demonstrated that $PM_{2.5}$ levels decreased significantly after the implementation of 100% smoke-free legislation in Argentina and provided the evidence needed to support such policies.

7.6.3.2 Chile

The use of wood is very common in the southern part of Chile, and Temuco is the most wood-smoke-polluted city in the region. The impact of ambient PM_{10} levels on daily mortality in Temuco was evaluated by Sanhueza et al. (2006). This study determined that there was a significant and positive association between the levels of ambient PM_{10} and daily mortality in Temuco owing to cardiovascular and respiratory diseases in people 65 years and older. PM_{10} in the region were highest in the fall–winter season.

The study by Sanhueza et al. (2006), however, did not determine the likely contribution from indoor air pollution to these outcomes, even though the researchers recognized that indoor wood combustion is significant in this city. It is important to emphasize this limitation because using only outdoor measurements as proxies of population exposure to PM means that indoor exposure is neglected. In communities where indoor air pollution from solid fuels is significant, this limitation should not be overlooked. Taking into account indoor exposure to PM would improve epidemiological modeling.

The effects of wood combustion inside homes in Temuco was later studied by Cortés and Ridley (2013) using computer simulations. In this study, the researchers simulated a Temuco residence using indoor wood burning. They evaluated the indoor PM_{10} and $PM_{2.5}$ levels assuming different permeability levels of the building envelope. Researchers acknowledged that using wood indoors has strong cultural roots, which do not correspond to typical economic market factors (e.g., price, cost). Ultimately, this study determined that it is very important to consider indoor air pollution sources to determine the health effects of PM.

Another study, conducted in Santiago, determined that relocating families from slums to public housing improved indoor air quality directly and also indirectly through the reduction of air pollution sources (Burgos et al. 2013). This study found that both indoor and outdoor $PM_{2.5}$ were significantly higher in slum houses than in public housing. This is one intervention approach that could be considered in other communities. Similarly, Barraza et al. (2014) conducted the first source apportionment of indoor $PM_{2.5}$ in Santiago. They found that indoor and outdoor sources each

contribute about half the $PM_{2.5}$ indoors and the main contributors were indoor cooking and traffic. Indoor $PM_{2.5}$ levels were also affected by socioeconomic status.

7.6.3.3 Guatemala

Indoor air quality and its health effects on rural Guatemalan communities has received considerable attention, compared with other communities (Boy et al. 2000, 2002; Bruce et al. 2007; Diaz et al. 2007; McCracken et al. 2007, 2009; Smith et al. 2006). Boy et al. (2000) compared the fuel efficiency of the traditional open three-stone fire with that of an improved *plancha*, a popular wood-burning stove used in western Guatemala. Although the improved stove showed efficiencies on a par with open fire, it also showed a reduction in fuel use. Overall, this study concluded that close attention must be paid to the long-term sustainability of improved stoves.

The Randomized Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE) is an intervention trial focused on Mayan women in Guatemala that evaluated the health effects linked to reductions in indoor air pollution from biomass use (Smith-Sivertsen et al. 2009). Before RESPIRE, other studies in the area had measured PM_{10} levels about 15 to 20 times those of the WHO guidelines (Naeher et al. 2000). The RESPIRE trial showed that using a *plancha* significantly reduced carbon monoxide levels, and reduced the risks for all respiratory symptoms reported in the study. However, no significant effects on lung function were found 12–-18 months after the intervention.

In a related RESPIRE study, Thompson et al. (2011) determined that using a chimney stove reduced wood smoke exposure in these Guatemalan communities and was associated with reduced, but not statistically significant, low-birth-weight occurrence. Before RESPIRE, Boy et al. (2002) first reported an association between biofuel use (wood smoke) and reduced birth weight in a human population. Further studies continue to provide evidence for health effects related to these exposures.

7.6.3.4 Mexico

Biomass is the primary cooking fuel in over two thirds of the households in rural areas of Mexico. Regalado et al. (2006) studied the effect of biomass burning on respiratory symptoms and lung function in rural Mexican women. They found that women cooking with biomass had increased respiratory symptoms and a slightly higher reduction in lung function (FEV1/FVC) compared with those cooking with gas.

Ramírez-Venegas et al. (2006) set out to determine the clinical profile, survival, and prognostic factors of chronic obstructive pulmonary disease (COPD) associated with biomass exposure and tobacco smoking. This study determined that women exposed to biomass at home developed COPD with clinical characteristics, quality of life, and increased mortality similar to those of tobacco smokers. In a subsequent

study, Ramírez-Venegas et al. (2014) assessed FEV1 in a Mexican cohort of patients with COPD associated with biomass or tobacco during a 15-year follow-up period. However, the results showed that the mean rate of decline in FEV1 was significantly lower for the COPD group exposed to biomass than for the group exposed to tobacco smoke.

7.6.3.5 Need for New Frameworks

The use of solid fuels for heating and cooking is a recognized challenge in the reduction of exposures to PM, both in developed and in developing countries. In the developed world, except for the poorest communities (e.g., Native Nations in the United States), wood is often a conscious choice, one among other alternatives (Champion et al. 2017). For developing communities, however, those alternatives may be limited and, in some cases, there is no choice at all. Proponents of cleaner alternatives for all these communities, especially developing communities, should consider the context and realities of each community before offering any solution or intervention. Reeve et al. (2013), for example, identified affective attachment to wood heating and socio-cultural norms as obstacles to the implementation of cleaner alternatives in Armidale, Australia.

Reducing indoor air pollution in developing communities has been the focus of many efforts. Many cooking stove interventions have taken place around the globe with marginal success (Clark et al. 2013), but fundamental scientific and technical knowledge must be coupled with contextual understanding of the local community.

A recent study proposed and applied a new framework for identifying heating alternatives for the Navajo Nation in the United States (Champion et al. 2017), a community that uses wood and coal for residential heating. This new framework incorporated three essential assessments: perception, cultural, and scientific, to provide a holistic solution for this community. Figure 7.11 shows the generalized

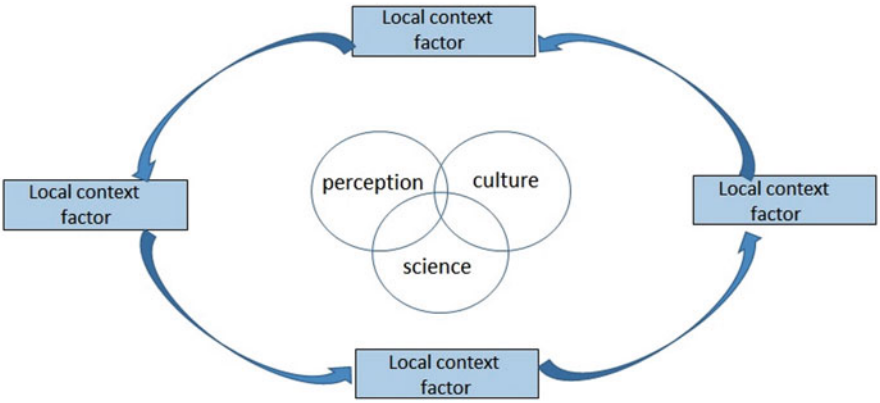

Fig. 7.11 Generalized framework for addressing indoor air quality issues

framework developed. The overall approach is to embed this three-prong assessment within a framework already in place in the community. This contextual framework is denoted by the outer circle in Fig. 7.11. Within that circle, the most important factors pertinent to that context (community) must be identified and integrated into the solution.

For the Navajo, the outer circle in Fig. 7.11 is represented by the Fundamental Navajo Law, with its corresponding factors. Details of that framework can be found in Champion et al. (2017). Developing communities with strong cultural identities are expected to have their own version of such laws, whether they are explicit or implicit. Outsiders must recognize that these factors belong to the community and cannot be substituted by opinions or recommendations from people not members of those communities. The best way forward is to earn the trust of these communities and to work closely with them to identify and address any solution.

This new framework could be applied to communities in Latin America, especially rural communities with strong cultural identities and long-standing traditions and behaviors that have a direct impact on their surrounding environments, including indoor air quality in their homes. These factors are often imported into cities when these rural populations migrate to urban centers, a trend expected to increase in the future.

7.7 Conclusions and Recommendations

This is a short exposition of the state of knowledge of outdoor and indoor air quality in Latin America. A more comprehensive review of the literature is required, but more importantly, more research is needed.

Latin American cities have ambient PM concentrations strongly influenced by local climate and socioeconomic conditions: good air quality in some coastal cities, poor air quality in some cities spread within narrow valleys. Large cities with long-standing air quality management plans (Mexico City, Sao Paulo, and Santiago) have shown significant improvements since the 1990s. This means that the urban transport systems of those cities have achieved more sustainable pathways. Some mid-sized cities with weaker local regulations have ambient concentrations higher than in the same country's largest city. Hence, in addition to climate and socioeconomic variability, a sustainable local governance does make a difference (e.g., Curitiba, Brazil, and Medellin, Colombia).

In Colombia, Bogota, and Medellin have areas with the highest annual average concentrations of airborne PM. High pollution events occur during dry seasons as a result of adverse meteorological conditions. Other cities and industrial areas are known to have poor air quality, but monitoring is absent, insufficient, or low-quality. Air pollution abatement plans have been implemented, but their results are limited because of insufficient enforcement capacity or lack of continuity of local government plans.

In southern Chile, most mid-sized cities are subject to the highest ambient $PM_{2.5}$ concentrations recorded in Latin America. Several factors explain this situation:

widespread urban poverty, poor building standards (especially subsidized housing for migrating dwellers), availability of cheap wood for heating and cooking, and climate conditions. Current government policies are the correct ones: subsidies for woodstove replacement and thermal refurbishment programs. However, given the scale of the problem, it will take several years to achieve compliance with ambient $PM_{2.5}$ air quality standards.

Several overall conclusions can be drawn from this summary of indoor air pollution. The most significant contributors to indoor air pollution and its related health effects in Latin America are tobacco smoke and biomass burning. Both sources affect the poor in addition to women, children, and the elderly in disproportionate ways. Both tobacco smoke and biomass smoke appear to have similar health effects. Proposed solutions or interventions should directly involve the affected populations to become sustainable in the long term. This exposition is designed to start a much-needed conversation on how to best address the need for healthy indoor environments and sustainable communities, especially for the poorest populations in Latin America. This conversation should involve researchers, governments, nongovernmental entities, industry, and community members in general, each with distinctive and critical roles to play.

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