PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
SCHOOL OF ENGINEERING

EFFECTIVENESS OF GREEN ROOFS AND WALLS TO MITIGATE ATMOSPHERIC PARTICULATE MATTER POLLUTION IN A SEMI-ARID CLIMATE

MARGARETH INDIRA VIECCO MÁRQUEZ

Thesis submitted to the Office of Graduate Studies in partial fulfillment of the requirements for the Degree of Doctor in Engineering Sciences

Advisor:
SERGIO VERA ARAYA

Santiago de Chile July 2021

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Thank you God for allowing me to live this life experience.
I dedicate this work to my mom Rita, mommy Josefa and my aunt Jose who are in heaven. To my children and my husband who sacrificed a lot for this. To all my family, I love you.

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OUTLINE OF THE THESIS

This thesis compiles the results of my doctoral work. The article format is the structure used in my thesis, which is based on three journal papers. One paper was published in 2018, while the others have been submitted for publication. The thesis has been organized into five chapters as follows:

Chapter 1: *Introduction*

This chapter presents the background regarding the air quality problem in different cities of the world and the potential of the implementation of green roofs (GRs) and green walls or living walls (GWs) to contribute to atmospheric decontamination by particulate matter (PM). This chapter also shows the knowledge gaps that lead to three research hypotheses. Finally, this chapter presents the research objectives and a synthesis of the research methodology.

Chapter 2: *Potential of Particle Matter Dry Deposition on Green Roofs and Green Walls Vegetation for Mitigating Urban Atmospheric Pollution in Semiarid Climates*

This chapter focuses on evaluating the capture potential of PM_{10} and $PM_{2.5}$ of nine species of vegetation that are the most used in extensive GRs and GWs in a semi-arid climate of Chile. The capture of PM is evaluated for single species (so-called monocultures). Two methods are carried out to measure PM capture, gravimetric and decay curve methods. The main results show statistically significant differences in the capture of PM_{10} and $PM_{2.5}$ among the nine species evaluated. *Sedum Album* showed the most significant PM capture potential. This chapter corresponds to a paper published in Sustainability in 2018.

Chapter 3: *Effects of biodiversity in green roofs and walls on the capture of fine particulate matter*

This chapter presents the results of combining different vegetation species used in extensive GRs and GWs to evaluate the effect of biodiversity on the $PM_{2.5}$ capture of GRs and GWs. The main conclusion is that plants' biodiversity improves $PM_{2.5}$ capture performance in the long term. This chapter corresponds to a paper submitted to the journal Urban Forestry & Urban Greening.

Chapter 4: *Green Roofs and Green Walls Layouts for Improving the Urban Air Quality by Particulate Matter*

The analysis of the effects of GRs and GWs at the neighborhood level, through a validated computational fluid dynamic simulation model, on the capture and concentrations of $PM_{2.5}$ is presented in this chapter. It is shown that the height of the buildings where GRs and GWs are located and vegetation coverage are crucial to improving GRs and GWs performance in capturing $PM_{2.5}$. GRs and GWs could remove up to 7.3% of the PM in Santiago's downtown. Some urban morphologies are suggested to guide urban planners and designers to promote $PM_{2.5}$ capture using GRs and GWs. This chapter is a paper submitted to Building and Environment.

Chapter 5: *Conclusions and Future Work*

In this last chapter, the main conclusions of the research are presented. Also, suggestions of future work are provided

ABSTRACT

Air pollution is an atmospheric phenomenon by which particles (solid/gas) contaminate the environment. The World Health Organization (WHO) considers air pollution as a substantial environmental risk for health, specifically for cities. Reducing the levels of air pollution can decrease morbidity related to strokes, lung cancers, and chronic and acute lung diseases, including asthma.

Industries such as construction, transportation, and consumption of fossil fuels, in other sectors, have contributed to increasing pollutant emissions to the urban environment. Pollutants, such as atmospheric particulate matter (PM), are considered highly harmful to people's health. Long-term exposure to PM is statistically associated with respiratory morbidity and mortality.

Thus, many cities have focused on improving urban air quality using different strategies, such as the implementation of green roofs (GRs) and green walls (GWs). Although there have been significant advances in research on the effect of GRs and GWs on urban air quality, there are still research gaps. These gaps related to identifying vegetation that favors the capture of PM, establishing strategies to enhance the PM capture capacity of different vegetation, and quantifying the impact of implementation of GRs and GWs at urban scales.

The main objective of this research is to analyze the effectiveness of GRs and GWs on mitigating air pollution by PM_{10} and $PM_{2.5}$ in improving urban air quality. The variability in capturing PM for GRs and GWs plants is evaluated and the influence of species biodiversity in capturing PM is investigated. The impact of GRs and GWs layouts on PM

capture and concentrations in a highly dense urban area with a Mediterranean climate is studied. In particular, GRs and GWs layouts, considering coverage and building heights where GRs and GWs are located, are two aspects of urban morphology analyzed.

The research methodology consists of quantifying the PM capture capacity for nine GRs and GWs species as monocultures and polycultures to investigate how PM capture varies among plants and due to biodiversity. Two methods are used to evaluate the PM capture, gravimetric analysis and decay curve. Based on the results of PM capture, a validated ENVI-met model is used to assess how urban morphology and GRs and GWs coverage influence PM capture and concentrations at a neighborhood scale of Santiagos' downtown.

The results in monocultures, GRs and GWs show that PM capture is highly species type dependent. $PM_{2.5}$ capture ranged from 0.09 $\mu g \cdot cm^{-2} \cdot h^{-1}$ for *Sedum Spurium P* to 1.32 $\mu g \cdot cm^{-2} \cdot h^{-1}$ for *S. Album*. Moreover, it found that biodiversity significantly increases the $PM_{2.5}$ capture compared to monocultures. In four of the five species studied, the $PM_{2.5}$ levels captured by the vegetation was higher in polycultures. Moreover, the results from ENVI-met modeling show that priority should be given to GRs for buildings lower than 10 m height to decrease $PM_{2.5}$ concentrations at pedestriam level. For GWs, the $PM_{2.5}$ abatement is favorable in all building configurations. In addition, the combined use of GRs and GWs can reduce up to 7.3% of $PM_{2.5}$ in Santiago's downtown compared to a base case scenario without GRs and GWs.

In conclusion, GRs and GWs are a valuable strategy to improve urban air quality, thus they should be implemented as a complement to other air quality mitigation strategies in large cities. *S. Album* outperforms the other species evaluated in capturing $PM_{2.5}$ either as monoculture or polyculture. It was also found that biodiversity enhance the $PM_{2.5}$ capture of GRs and GWs. It is recommended the polycultures of *L. Spectabillis, Lavandula Angustifolia* and *S. Album* for GRs and *Sedum Palmeri, S. Album* and *Sedum Spurium P* for GWs to maximize the effectiveness of GRs and GWs to capture $PM_{2.5}$. On the other hand, the implementation of GWs has a greater impact on $PM_{2.5}$ abatement than GRs due to their proximity to the emission source. It is suggested to implement GRs on buildings up to 10 m height and coverage between 50% and 75%. For GWs, a coverage of 25% is recommended.

These results provide scientific support for the inclusion of GRs and GWs in public policies and urban development plans in order to improve urban air quality. Moreover, the methodologies used in this research can also be applied to other species and urban morphologies to identify the optimum combinatory of vegetation species and layouts to capture PM in the urban environment.

Keywords: Green roofs (GRs), green walls (GWs), particulate matter with an aerodynamic size less than or equal to 10 µm (PM_{10}), particulate matter with an aerodynamic size less than or equal to 2.5 µm ($PM_{2.5}$), dry deposition, PM capture, PM deposition, urban air quality, GRs vegetation, GWs vegetation, biodiversity, phytofiltration, CFD, ENVI-met, and urban morphology.

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Chapter 2. Viecco, M., Vera, S., Jorquera, H., Bustamante, W., Gironás, J., Dobbs, C., & Leiva, E. Potential of particle matter dry deposition on green roofs and living walls vegetation for mitigating urban atmospheric pollution in semiarid climates. Sustainability, 10 (7), 2431. July 2018.

Chapter 3. Sergio Vera, Margareth Viecco and Héctor Jorquera. Effects of biodiversity in green roofs and walls on the capture of fine particulate matter. Urban Forestry & Urban Greening, 63, 127229. June 2021.

Chapter 4. Green Roofs and Green Walls Layout and Coverage to Improve the Urban Air Quality by Particulate Matter. Building and Environment, 204, 108120. July 2021.

1. INTRODUCTION

Air pollution is defined as the presence in the atmosphere of particles, gases, and pollutant vapors incorporated in the air in sufficient quantities to alter its quality, which implies impacts to human health, animals, ecosystems, and built environment (Alfaro, 1999). There are natural and human-related activity sources (i.e. construction, industry, transportation, fossil fuel consumption). Depending on their concentration in the air, pollutants could severely impact human health, with short, medium, and long-term implications (Héctor Jorquera, 2010).

The contaminants considered most harmful to people's health are measured routinely. Emissions of particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_X), volatile organic compounds (VOC), sulfur oxides (SO_X), tropospheric ozone (O_3) and scale global study of greenhouse gases (GHG) are usually reported (Héctor Jorquera, 2010). Specifically, the PM has been considered by the World Health Organization (WHO) as a contaminant with severe effects on human health (WHO, 2016c). For example, chronic exposure to air contaminated with particles smaller than 10µm causes cardiopulmonary system diseases and deaths (Chow et al., 2006; Gurjar et al., 2010; Pope III et al., 2002).

1.1 Atmospheric Particulate Matter

Atmospheric particulate matter (PM) is a mixture of organic and inorganic substances of different sizes that are suspended in the air. These particles come mainly from physical, chemical and mechanical processes.

The breathable PM are solid particles suspended in the air with aerodynamic diameters smaller than 10 µm, which correspond to a mixture of organic and inorganic substances.

The toxicity level of this pollutant depends on the source and the size of the particles. The PM has been classified according to their size as ultrafine, fine, and coarse (Héctor Jorquera, 2010).

a) Coarse atmospheric particulate matter (PM_{10})

PM_{10} represents all the particles with an aerodynamic size less than or equal to 10 μm. This originates from mechanical processes and mainly corresponds to soil particles eroded by the wind, fugitive dust from roads and industrial activities, mining, agriculture, and construction. It also includes marine spray, pollen particles, insects and plant remains (Pooley & Mille, 1999). PM_{10} spends less time in suspension than fine and ultra-fine.

b) Fine atmospheric particulate matter ($PM_{2.5}$)

$PM_{2.5}$ is produced mainly by physical and chemical processes such as combustion, the condensation of metallic and organic vapors, and the neutralization of acid gases (SO_X and NO_X emissions). Their size affects the respiratory and cardiac systems (Pope & Dockery, 2006).

There are two types of $PM_{2.5}$, the fine and ultra-fine. The fine PM represents all particles with an aerodynamic size less than or equal to 2.5 μm but greater than 0.1 μm. These are mostly particles of sulfates and nitrates of ammonium and organic carbon, which have slow sedimentation processes and are transported over long distances. The ultra-fine particle matter corresponds to particles with an aerodynamic size less than or equal to 0.1 μm but greater than 0.01 μm, mainly from the condensation of supersaturated gases (SO_2, NH_3, and NO_X).

PM_{10} and $PM_{2.5}$ is usually compared with the diameter of human hair to express their size. The diameter of human hair is between 5 and 7 times larger than PM_{10} and between 20 and 28 times larger than $PM_{2.5}$ (EPA, 2017).

1.2 Impact of PM on Human Health

Air pollution has been related to different negative impacts on people's wellbeing, mainly health-related problems. Exposure to environments contaminated with PM has been associated to increased visits to the emergency rooms, respiratory diseases and damage at the pulmonary tissue level, decreased work activity, chronic diseases, premature mortality, lung cancer, respiratory morbidity and mortality (Anderson, Thundiyil, & Stolbach, 2012). Multiple investigations show the effects of air pollution on human health (Cakmak, Dales, & Vidal, 2007; Díaz-Robles et al., 2014; Pascal et al., 2013; Romero-Lankao, Qin, & Borbor-Cordova, 2013; Yafei Wang, Bakker, de Groot, & Wörtche, 2014; Wiseman & Zereini, 2009). For example, approximately 3,000 excess deaths in a month associated with poor air quality occurred in London (UK) in 1952 (Bell & Davis, 2001). Similarly, in China during 2010, outdoor air pollution contributed to 1.2 million premature deaths (Lozano et al., 2012).

The studies cited above show a relationship between poor air quality by PM and people's health. Therefore, it is expected that by reducing pollution in the atmosphere, the effects are reduced. An example of this is evidenced in a study carried out in Beijing (China) that showed a 10% decrease in PM_{10} concentration could reduce the mortality rate up to 8% (He, Fan, & Zhou, 2016).

In the case of Chile, high concentrations of various pollutants, including particulate matter, have been associated with the development of diseases related to the lifestyle of people (Franck, Leitte, & Suppan, 2014; Garcia et al., 2014; Leiva, Santibañez, Ibarra, Matus, & Seguel, 2013; Toro A., Morales S., Canales, Gonzalez-Rojas, & Leiva G., 2014) and with mortality (Cakmak et al., 2007).

Other impacts of exposure to this pollutant are damage to ecosystems, agriculture, infrastructure, cultural heritage and loss of visibility (Pope & Dockery, 2006; Vedal, 1997). However, the most severe negative effects are on people's health, mainly caused by $PM_{2.5}$ in suspension (Andersen et al., 2015) that is considered more harmful. Children and the elderly has been identified as vulnerable groups to PM exposure (Asenjo, 2011). Table 1-1 presents a list of studies conducted in different countries regarding the effects of PM contamination.

Table 1-1 Effects of exposure to PM pollution

Effect	Cause	Age	Region	Source
Premature mortality	All cause	Under 70 years	Canada, USA, Caribbean, Latin America, Africa, Western Europe, Eastern Europe, Russia, Middle East, China, India, Asia, Oceania and Global	(Burnett et al., 2018)
		Under 70 years	Global	(WHO, 2016d)
Hospital admissions	Asthma	All cause	USA	(Chow et al., 2006)
	Cardiovascular	All cause	Canada	(Vanos, Hebbern, & Cakmak, 2014)
	Dysrhythmia	Older adult	USA	(Chow et al., 2006)
Activity restriction	All cause	Older adult	USA	(Hsu et al., 2012)

According to WHO, chronic exposure to PM leads to an increased risk of premature death from a heart attack, stroke, respiratory infections, and lung cancer. For this reason, based on WHO recommendations, PM_{10} and $PM_{2.5}$ monitoring are taken periodically and controlled in different countries (WHO, 2016b) including Chile.

1.3 PM Pollution in Latin America and Chile

According to a study by the WHO, using the information of PM concentration levels in 1600 cities of 91 countries between 2008 and 2013, Latin America is a region with highly air contaminated cities. Among 50 studied Latin American cities, Santiago (Chile) was the most polluted of higher-income cities. At the same time, Mexico turned out to be the most polluted among low and middle-income cities in this region (Martinez, 2014).

Despite PM_{10} and $PM_{2.5}$ concentrations have decreased during the last 27 years in Chile (Mena-Carrasco et al., 2014), several cities exceed the PM limits defined by the WHO (OECD, 2016). According to the IQAir AirVisual 2019 World Air Quality Report in Latin America, Chile has 8 of the 10 cities with the greatest problems of air quality, and Chile has 18 of the 20 most polluted cities in South America. In this study, Coyhaique (Chile), Osorno (Chile), Padre de las Casas (Chile), Providencia (Chile) and Santiago (Chile) are the five most polluted urban areas in South America (CNN, 2020).

The Center for Sustainable Urban Development (CEDEUS) reports on the pollution of Chilean cities between 2016 and 2018, showing that 12 cities had concentrations of $PM_{2.5}$ above the WHO international standard 10 $\mu g \cdot m^{-3}$. Coyahique and Osorno presented $PM_{2.5}$ concentrations above 40 $\mu g \cdot m^{-3}$; Valdivia, Temuco and Chillan between 30 $\mu g \cdot m^{-3}$ and 40 $\mu g \cdot m^{-3}$; Talca, Rancagua and Santiago between 20 $\mu g \cdot m^{-3}$ and 30 $\mu g \cdot m^{-3}$; Viña del Mar, La Serena, Copiapó and Antofagasta between 10 $\mu g \cdot m^{-3}$ and 20 $\mu g \cdot m^{-3}$ (CEDEUS, 2019).

In addition, 88% of the environmental quality monitoring stations installed in Chile present $PM_{2.5}$ concentrations higher than the standards defined by the WHO (Visión UC, 2016). According to the National Air Quality Information System (SINCA), two main sources of generation of PM_{10} and $PM_{2.5}$ are identified in Chilean cities (MMA, 2018). The first comes mainly from mining activities with average concentrations of 60 $\mu g \cdot m^{-3}$. The second is transport and improper combustion of firewood. Concentrations of 30 μgm^{-3} for the central zone and 60 $\mu g \cdot m^{-3}$ for the southern zone have been measured. In Chile, a large part of the population is exposed to severe concentrations of $PM_{2.5}$ that exceed 35 $\mu g \cdot m^{-3}$ (OECD, 2016).

Consequently, Chilean authorities have implemented several programs to mitigate the air pollution of Chilean cities due to PM and especially by $PM_{2.5}$. These programs include emission controls in fixed sources, environmental monitoring, vehicle restrictions, use of sustainable technologies, and vegetation at the urban level, among others (Criollo Céspedes, 2015). For example, three decontamination plans have been applied (Congreso

Nacional de Chile, 2013) in the Metropolitan Región of Chile during the last 25 years to improve the air quality. They have included different strategies to reduce air pollution such as the prohibition of agricultural burning in winter, change of public transportation fleet, restriction to non-catalytic vehicles, banning the use of open chmineys for household heating, the inclusion of natural gas, and a new integrated public transport system called Transantiago, among others. All these actions have contributed to improving the air quality, but there are still episodes that are intensified by the climatic conditions in winter. This indicates that more decisive actions and initiatives are required to have a substantial impact in the short, medium and long term.

1.4 Green Infrastructes Initiatives in the World to Mitigate PM Impacts

Taking into account the air pollution by PM problems in the urban zones, different countries have implemented initiatives that consider the use of green infrastructures (GI) technologies.

For example, China's clean air action plan includes the control of urban green spaces, the installation and maintenance of municipal gardens, greening of roadsides, and increasing green coverage, among others (Zhong, 2013). In 2015, France promulgates a legislation that mandates the roofs of all new buildings must be partially covered with green roofs (GRs) and solar plants or panels (Gonzalez, 2015). Similarly, new buildings in Denmark must have some type of vegetation covering. Denmark also plans to cover the old roofs with vegetation in order to become carbon neutral by 2025 (López, 2016). Similarly, Switzerland implemented a Federal Law so that new buildings have green elements on their exterior facades.

In North America, Toronto (Canada) established a law to implement GRs in shopping centers, corporative buildings, homes and residences. Also, the Régie du Bâtiment du Québec has published guidelines and regulations governing the construction of GRs (Paradis, 2015).

In Latin America, the Regional Plan of Action on Atmospheric Pollution motivates the implementation of ecological technologies (PNUMA, 2014). In Buenos Aires, Argentina, Law 4428 of GRs and Terraces (non-mandatory) encourages the use of GRs (López, 2016). In Chile, no specific initiatives have been presented for the implementation of GRs and GWs, however, policies such as the Santiago Verde plan oriented to the greening of public areas have been promoted. (Congreso Nacional de Chile, 2013).

The initiatives mentioned below are oriented towards implementing GI technologies that fulfill ecological functions such as considering the environmental potential of the vegetation.

The mentioned initiatives above have been oriented to the implementation of urban vegetation, considering the ecosystem services of the plants.

1.5 Potential of Urban Vegetation for Atmospheric Decontamination

The vegetation, in general, has a phytoremediation potential, which consists of a biological mechanism of the plants and their microorganisms to purify various pollutants of the environment from biochemical processes (Delgadillo, 2011; H. Yang & Liu, 2011).

According to the ecosystem in which they live (soil, water, air), there are several types of phytoremediation: phytofiltration, phytovolatilization, phytodegradation, phytoextraction and rizofiltration (Pilon-Smits, 2005).

NASA, in 1989 found that by arranging different species of trees in controlled environments with different emissions of pollutants, some trees captured up to 87% of the toxic compounds in 24 hours (Wolverton et al., 1989). This finding was part of the NASA project to respond to the question “How does the Earth maintain a breathable atmosphere?”. The phenomenon responsible for reducing air pollution by trees is the phytofiltration of air. This is the process of using the morphological characteristics of plants to adsorb and capture significant amounts of air pollutants through the surface of its leaves and stems (Weyens et al., 2015). The process is as follows: the contaminants are deposited on the surfaces of their leaves and stems, they are adsorbed, and a portion of these are captured or sequestered by the plant, which, together with its microorganisms, can detoxify part of the contaminants through of degradation, transformation or sequestration. The rain transport the pollutants down; thus, they come into contact with their roots, continuing with the rizofiltration process (Weyens et al., 2015) (See Figure 1-1).

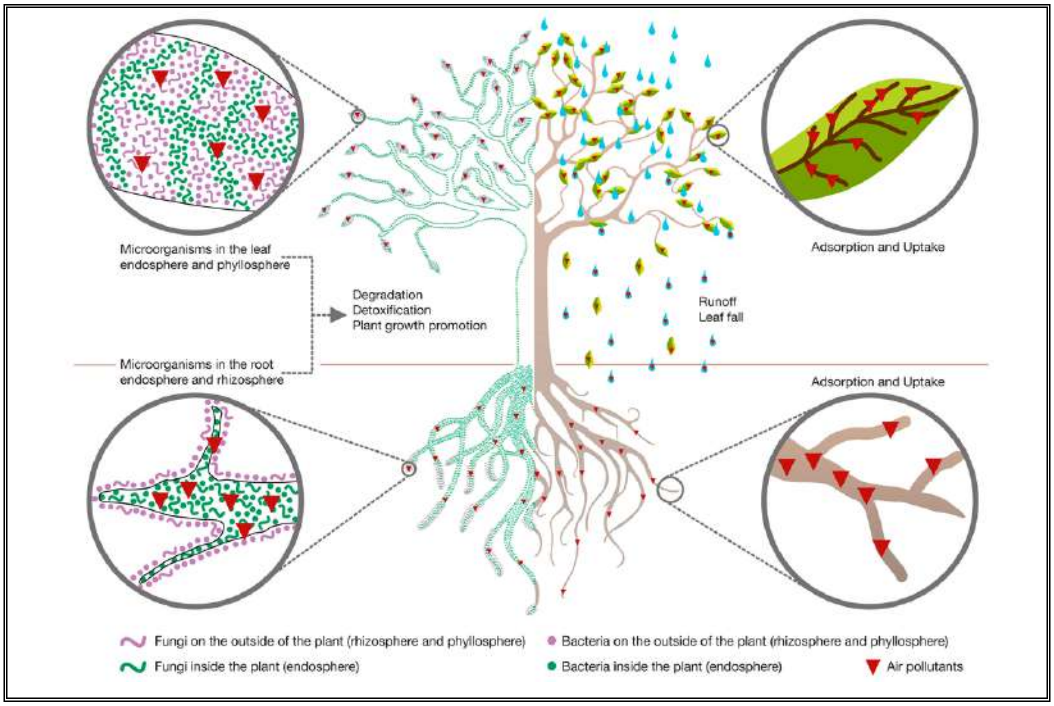


Figure 1-1 Phytofiltration process in the plant
(Weyens et al., 2015)

Each species has a different contaminant capture potential that allows it to work as an air filter, so it is necessary to identify the species or set of species that maximize its potential of decontamination (Papaioannou, 2013).

Different studies have shown that urban vegetation plays an essential role in the mitigation of pollution by PM in urban air. The PM is deposited on its leaves and initiated the biochemical process on these, allowing its adsorption and capture (Chen, Liu, Zou, Yang, & Zhang, 2015; Dzierżanowski, Popek, Gawrońska, Sæbø, & Gawroński, 2011; D. Muñoz, Aguilar, Fuentealba, & Préndez, 2017; Song et al., 2015; Weyens et al., 2015).

In addition, the tree species can decrease the concentration of atmospheric PM through deposition and capture. Figure 1-2 shows the PM capture by deposition of some trees, shurbs and climbing vegetation such as *Pinus Sylvestris*, *Hedera Helix, Pinus Tabuliformis, Juniperus Formosan, Euonymus Japonicus*, among others.

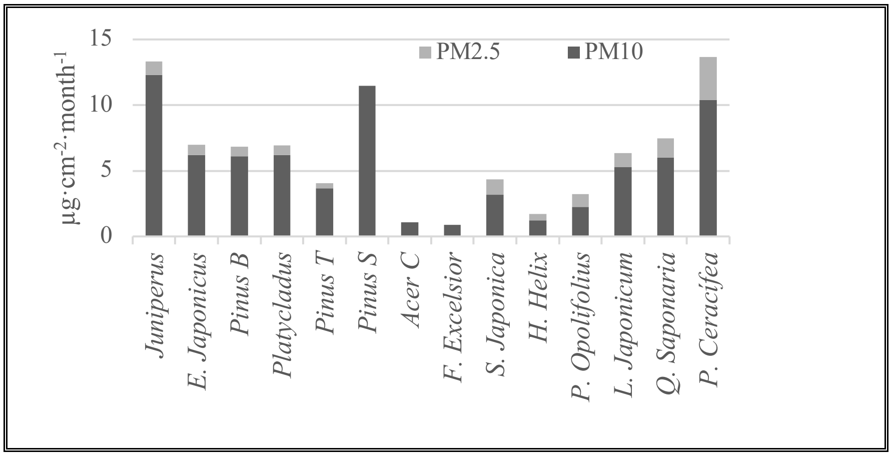


Figure 1-2 Potential for the deposition of trees, shrubs and climbing vegetation according to particle size
Created based on data of Dzierżanowski et al., (2011); Przybysz, Hanslin, & Gawroski, (2014) and Song et al., (2015).

Despite the evidenced benefits in PM capture of trees, their use to mitigate air pollution requires big spaces to be planted, which has become a limited resource due to the densification of cities (Peschardt, Schipperijn, & Stigsdotter, 2012; Song et al., 2015). For this reason, other types of green infrastructure (GI) like grasses, shrubs, hedges, GRs and green walls (GWs) have been identified as a valuable strategy to mitigate air pollution and improve urban air quality (Berardi, GhaffarianHoseini, & GhaffarianHoseini, 2014). These alternatives, especially GRs and GWs, allow using gray areas such as building envelope surfaces to implement vegetation on them.

1.6 Green Roofs and Green Walls

GRs and GWs are technologies that employ vegetation on building façades. Therefore, the use of green areas is preserved and promoted. Additionally, GRs and GWs provide other benefits in an urban environment such as thermal insulation of buildings (DiGiovanni, Gaffin, Montalto, & Rosenzweig, 2010; Feng & Hewage, 2014; Malys, Musy, & Inard, 2014; Wong, Tan, Tan, & Wong, 2009), retention of surface run-off at the urban level (DiGiovanni et al., 2010), reduce urban heat islands (Krüger, 2015; Yupeng Wang, 2015) and potential for contaminant capture (Chen et al., 2015; Papaioannou, 2013), among others.

This infrastructure can be located in roofs and walls. They are formed by a substrate, drainage, vegetation, irrigation system and other layers (i.e waterproofing, insulation). Figure 1-3 shows a detail of the typical structure of GWs and extensive GRs.

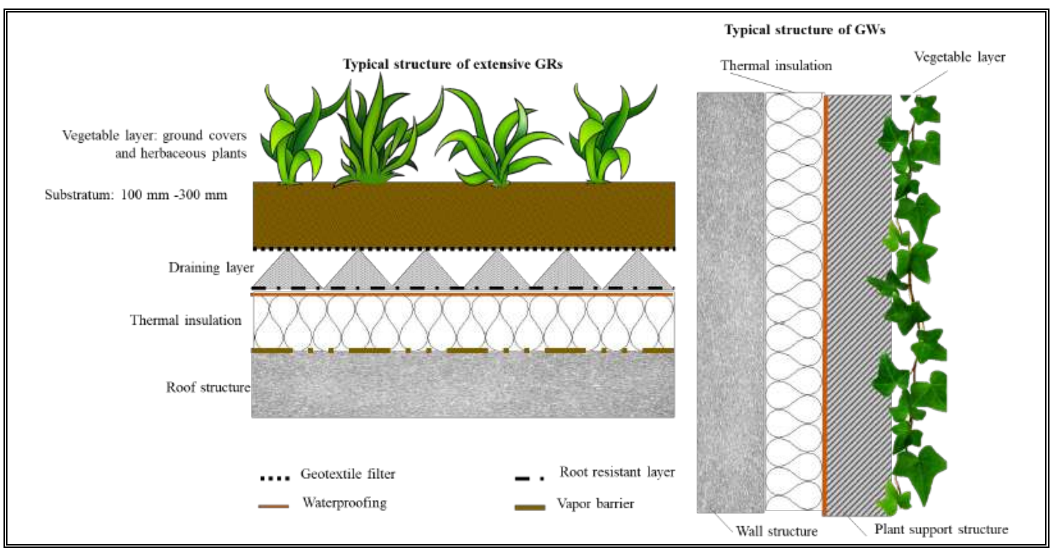


Figure 1-3 GRs and GWs structure
(Own elaboration)

1.7 Potential of GRs and GWs for Urban Air Decontamination by PM

Some authors agree that GRs and GWs act as passive filters of air contaminated with PM (Papaioannou, 2013; Song et al., 2015; Speak, Rothwell, Lindley, & Smith, 2012a; Jun Yang, Yu, & Gong, 2008), but they are not as effective as street trees due to lower surface roughness lengths (Speak et al., 2012a). However, GRs and GWs can be used to supplement the control of air pollution by urban trees (Jun Yang et al., 2008). Additionally, GRs and GWs vegetation are an excellent alternative as a filtration mechanism for contaminants in indoor environments (Papaioannou, 2013).

For example, Speak et al. (2012a) found that species used in vegetated roofs such as *Agrostis stolonifera, Festuca Rubra, Plantago lanceolata* and *Sedum Album* could capture up to 2.3% of the PM_{10} in a year (Speak et al., 2012a). An experimental study in Singapore, before and after the installation of 4000 m^2 of GRs, showed that GRs can reduce pollutants in the air, but it is difficult to extrapolate the results to other places or a larger scale (Tan & Sia, 2005).

On the other hand, the PM capture potential of some types of *Sedum,* grasses (i.e. *Festuca Rubra*) and climbing species (i.e. *Hedera Helix Peda*ta) is known (Dzierżanowski et al., 2011; Popek, Gawrońska, Wrochna, Gawroński, & Sæbø, 2013; Speak et al., 2012a). However, the capture potential of most plants used in GRs and GWs remains unmeasured.

Although the state-of-the-art concludes that GRs and GWs can capture PM and contribute to mitigating air pollution in urban areas, there is still much to understand. For example, GRs and GWs interact with the surrounding environment, triggering complex physical-chemical processes that might influence the vegetation's potential to capture PM. Therefore, more research is needed to understand and define GRs and GWs vegetation designs to capture PM based on different geographic locations (X. Zhang, Shen, Tam, & Lee, 2012a) and urban microclimates.

Another aspect to be studied is how to enhance the performance of GRs and GWs in PM capture. In this regard, Cook-Patton & Bauerle, (2012) indicate that vegetation can improve performance in different performance aspects due to biodiversity. For example, biodiversity in GRs vegetation can increase leaf density, rooftop insulation, reflectance, and cooling from evapotranspiration (Alexandri & Jones, 2008; Kumar & Kaushik, 2005; Verheyen et al., 2008). Based on this, it is expected that plant biodiversity enhances GRs and GWs to improve PM capture.

In addition to knowing the PM capture potential of the vegetation and how to improve its performance, it is necessary to understand the effect of urban morphology and location of GRs and GWs on PM capture and concentrations at the urban scale. Different authors suggest that the use of computational models is very useful (Tan & Sia, 2005) and facilitate the interpretation of the information (Abhijith et al., 2017; X. Zhang et al., 2012a).

1.8 Modelling of PM Capture of GRs and GWs

Several numerical modeling studies about the impact of vegetative envelopes on the urban air quality are found in the literature. For instance, the numerical model Urban Forest Effects (UFORE), was used by Deutsch et al., (2005), who found that GRs on Washington, D.C. (USA) can remove 58 metric tons of air pollutants in a year. Jun Yang et al. (2008) analyzed the removal of air pollutants on 19.8 Ha of GRs in Chicago. They found that 1,675 kg of pollutants are removed in a year, corresponding to 52% of O_3, 27% of NO_2, 14% of PM_{10} and 7% of SO_2 Using UFORE model. Another study that evidenced a positive impact of GRs was developed in Toronto (Canada), where 108 Ha of GRs can remove 7.87 metric tons of air pollutants per year (Currie & Bass, 2008). The main limitations of UFORE are that it was developed specifically for trees and shrubs not for

GRs and GWs, furthermore, it did not consider the plant metabolism, it only uses a deposition model.

Additionally to these limitation, there is difficulty understanding the deposition processes and dispersion of pollutants considering the climate variables present in each study case. Computational Fluid Dynamics models (CFD) have been used to address this issue. CFD models has been used for modeling outdoor environments, including climatic variables (i.e. wind, temperature, precipitation) and pollutants sinks and sources. These models allow to test and evaluate the benefits of sustainable architecture and urban design, such as green technologies based on a micro-climate simulation, considering plant interactions among the surface, the atmosphere and the urban environment (Bruce, 2008). They have been used in different micro-climate modeling to analyze the behavior of plants on urban structures, both thermal and pollutant reduction. Table 4-1 in chapter 4 shows a summary of related investigations made with different numerical models, including CFD models. These studies evaluate the impact of urban air quality of different GI. In particular, Table 4-2 shows several studies on the impact of GRs in removing PM from urban air using different CFD simulation tools such as Open FOAM, WRF, PHOENICS and ENVI-met.

1.9 Statement of the Problems

It is known that vegetation has the potential to capture pollutants through the phytoremediation process. It has also been shown that different species of urban trees significantly contribute to improving the urban air quality by removing PM. However, there are limitations such as the reduced availability of urban spaces to plant trees and problems caused by adapting existing urban spaces to allocate them (i.e. construction works, blocking sidewalks and roads). In contrast, a large number of building surfaces where GRs and GWs could be installed to capture PM are available at the urban level.

GRs and GWs have multiple benefits, including PM capture. Based on research with trees, it is expected that GRs and GWs show significant differences to capture PM among species, but it remains to be investigated. Moreover, plant biodiversity improves several GRs and GWs performances (i.e. less irrigation and maintenance, increase leaf density); thus, it should also enhance the ability of GRs and GWs to capture PM. However, to the author's best knowledge, the literature does not show evidence in this regard.

Despite the research advances on capture of PM by GRs and GWs, it is needed to evaluate their effect at the urban level. However, the performance of GRs and GWs vegetation to capture PM and modify the urban PM concentrations could be affected positively or negatively by urban morphology, climatic conditions, location and coverage of GRs and GWs, PM emission source location, and other spatiotemporal factors. For this reason, it is necessary to evaluate the decontamination potential of the vegetation used in GRs and GWs in each geographic location or specific climatic characteristics. The literature suggests the use of CFD models is useful for addressing these issues. Therefore, research based on validated CFD models needs to be carried out to evaluate different urban scenarios to generate to generate design recommendations for GRS and GWs to improve the urban air quality by PM at neighborhood and city scales.

1.10 Hypotheses

Based on the problems stated in previous section, the following hypotheses sustain and guide this doctoral research:

H1. Among plant species most used in GRs and GWs in Santiago (Chile), the Sedum family are the most effective in contributing to urban atmospheric decontamination by capturing PM_{10} and $PM_{2.5}$.

H2. The plant species biodiversity significantly improves the performance of GRs and GWs to capture PM in comparison with, and proper combinations of plants can favors the capture of PM.

H3. A reduction of air pollution by $PM_{2.5}$ of 15% is achieved with the installation of GRs and GWs on the most appropriate surfaces of an urban area.

1.11 Objectives

The main objective of the proposed research is to analyze the effects of the use of GRs and GWs on the capture of atmospheric PM_{10} and $PM_{2.5}$ in an urban area characterized by high air pollution and semi-arid climate. The specific objectives are the following: (O1) To quantify the capture capacity of PM of GRs and GWs vegetation and identify the species that can generate the most significant contribution to the capture of PM. (O2) To evaluate the effect that biodiversity can generate on the capture of PM of the vegetation used in GRs and GWs considering different mixes of species. (O3) To analyze, through a validated CFD model, GRs and GWs layouts that promote the capture of PM in an urban environment. Figure 1-4 shows a representation that relates the hypotheses, objectives and papers developed in this doctorate research.

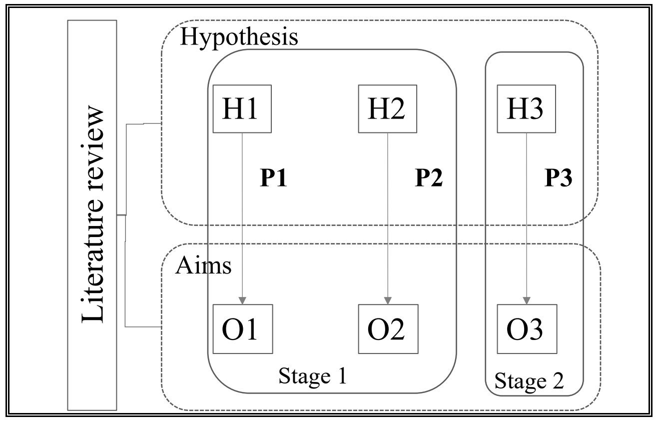


Figure 1-4 Directionality of the research

1.12 Research Methodology

The research methodology was established in two stages. The first stage is based on experimental laboratory work to test hypotheses 1 and 2. This stage aims to quantify the PM vegetation capture of plants used in GRs and GWs in the semiarid climate of Santiago of Chile. On the other hand, the second stage is based on CFD modeling to evaluate the effect of GRs and GWs on PM capture and concentrations at a neighborhood level. This stage was developed to test hypothesis 3.

Stage 1: Laboratory work

From the results of a survey of GRs and GWs in Chile, which was carried out prior to this investigation (Vera et al., 2014), nine of the species most used in GRs and GWs in Chile were selected to analyze their PM capture potential. These species were planted under optimal conditions in a nursery at the Laboratory of Vegetative Infrastructure of Buildings (LIVE for its acronym in Spanish) at the Pontificia Universidad Católica de Chile. The plants were subjected to controlled conditions (i.e. temperature, relative humidity, well-mixed air) with high PM concentrations, and the capture of PM_{10} and $PM_{2.5}$ of each species was measured by the gravimetric separation method. Chapter 2 of this thesis shows the methodology in detail.

To test hypothesis 2, plant species diversity used in GRs and GWs with a high potential for capturing $PM_{2.5}$, were combined in several mixes and configuration designs. The capture of $PM_{2.5}$ of each vegetation and mix was quantified using gravimetric separation of particles as described in chapter 2. At the same time, the exponential decay curve method was carried out to evaluate the impact of mixes on $PM_{2.5}$ air concentrations. Chapter 3 of this thesis describes the procedures in detail.

More details about the process in stage 1 are presented in chapter 2 and 3.

Stage 2: CFD modeling of an urban area

Analysis of different CFD models and other numerical tools was studied to identify the most appropriate tool to perform this research stage, which focuses on evaluating the impact of GRs and GWs on the $PM_{2.5}$ concentrations at Santiago's downtown. ENVI-met is selected because it considers essential characteristics that affect the performance of plants, such as the metabolism, the foliar area index, evapotranspiration, among others. It was necessary to validate the ENVI-met model developed with measured pollutant information from the Independencia monitoring station.

A multi-factor analysis was performed to determine the optimal location and configuration that should be considered to implement GRs and GWs in highly polluted urban areas. Two main GRs and GWs layout factors were considered, coverage ratio (Cr) and building height where GRs or GWs are located. Two scenarios were implemented in the CFD model and PM capture by vegetation and PM concentration were compared. The two cases were the actual situation (as the base case) and a greener case, including GRs and GWs. The CFD model and cases evaluated are presented in Chapter 4 of this thesis.

2. Potential of Particle Matter Dry Deposition on Green Roofs and Green Walls Vegetation for Mitigating Urban Atmospheric Pollution in Semiarid Climates

Margareth Viecco, Sergio Vera, Héctor Jorquera, Waldo Bustamante, Jorge Gironás, Cynnamon Dobbs and Eduardo Leiva.

Abstract:
In the last two decades, the incorporation of green roofs and living walls in buildings has increased significantly worldwide because of their benefits such as building energy savings, promoting biodiversity, controlling water run-off, mitigating urban heat island effect, improving indoor and urban air quality and connecting people with nature. However, few studies have quantified the impact of green roofs (GRs) and living walls or green walls (GWs) on mitigating air pollution, especially in semiarid climates where airborne particle matter (PM) levels are high. Therefore, the aim of this paper is quantifying the dry deposition of PM_{10} and $PM_{2.5}$ by several vegetation species commonly used in GRs and GWs in semiarid climates. Five species *(Pitosporum Tobira, v. n, Lavandula Angustifolia, Lampranthus Spectabillis, Sedum Album* and *Sedum Reflexum*) for GRS and four species (*Aptenia cordiflora, Erigeron Karvinskianus, Sedum Palmeri* and *Sedum Spurium P.*) for GWs were tested in an experimental facility - through washing, filtering and weighing - to quantify the dry deposition of $PM_{2.5}$ and PM_{10} on vegetation leaves as well as PM captured by the leaf wax. The main result is that a significant amount of PM is deposited on the typical vegetation used in GRs and GWs in semiarid climates. Therefore, these green infrastructures (GI) can contribute to mitigate air pollution. However, large differences in PM dry deposition were found among species, ranging from

0.09 to 1.32 μg·cm^{-2} for $PM_{2.5}$, 0.48 to 4.7 μg·cm^{-2} for PM_{10} and 0.41 μg·cm^{-2} to 25.6 μg·cm^{-2} for leaf wax. The species that showed the highest potential to capture PM were *S. Album, S. Reflexum, S. Palmeri* and *L. Spectabillis*.

Keywords: Particulate matter (PM); air pollutants; green roofs; living walls; air quality; sustainable urban development, vegetation species; $PM_{2.5}$; PM_{10}; wax; dry deposition; PM capture

2.1. Introduction

Nowadays, air pollution is considered a major environmental risk for people living at many cities worldwide (MMA, 2012). Among the air pollutants present in urban areas, respirable particulate matter (PM) is associated to severe health problems such as lung cancer and premature mortality as well as emergency room visits and morbidity (Díaz-Robles et al., 2014). Pope et al. (Pope & Dockery, 2006) state that long-term exposure to particle matter smaller than 10 μm increases the risk of heart and lung diseases as well as lung cancer, reducing life expectancy.

As a response to that burden of disease, authorities at urban areas have proposed different regulations to improve ambient air quality: tighter emission levels for mobile and stationary sources, cleaner fuels, promoting public transportation versus private cars, etc. More recently, authorities have started encouraging the use of urban vegetation for reducing air pollution (Gulsrud, Hertzog, & Shears, 2018). Urban green infrastructures such as roadside and park trees, vegetation barriers, green roofs (GRs) and green walls (GWs), can reduce the concentrations of different air pollutants through the phytofiltration mechanism (Weyens et al., 2015). It is known that the leaves' surface and stems adsorb significant amounts of air pollutants. Specifically, for the case of PM, the particles suspended in the air are deposited or accumulated on the leaf surfaces. Although a fraction of deposited or accumulated PM is resuspended by wind, another part of PM remains attached to the plant. Moreover, particles with aerodynamic size less than 0.2 µm can enter through the stomata thus are permanently captured (Ottel, van Bohemen, & Fraaij, 2010a; Song et al., 2015). Rainfall, on the other hand, washes down pollutants so that they come into contact with the roots, where the depuration process occurs through the roots in the soil (Weyens et al., 2015). In this paper, the evaluation of capture potential of PM by GRs and GWs is measured by the PM deposited on the leaf surface.

Urban green infrastructure plays an important role in the mitigation of PM contamination in urban areas and several studies have demonstrated the PM mitigation potential of trees, shrubs, grasses, herbaceous plants, climbers and lianas (Chen et al., 2015; D. Muñoz et al., 2017; Przybysz et al., 2014; Song et al., 2015). Dzierżanowski et al. (Dzierżanowski et al., 2011) showed that four species of roadside trees (*Acer campestre L., Fraxinus excelsior L., Platanus × hispanica Mill. ex Muenchh. 'Acerifolia', Tilia cordata Mill*), three species of shrubs (*Forsythia×intermedia Zabel, Physocarpus opulifolius L. Maxim., Spiraea japonica L.*) and one climber species (*Hedera helix L.*) were able to purify the urban air through the dry deposition of PM on the leaves. The maximum deposition of PM_{10} reported in (Dzierżanowski et al., 2011) was approximately 25 $\mu g \cdot cm^{-2}$ in two growing seasons monitoring. Additionally, this study found that PM deposited varies significantly among the species evaluated, which agrees with the findings of others researches such as (Chen et al., 2015; Przybysz et al., 2014; Song et al., 2015). Moreover, Dzierżanowski et al (Dzierżanowski et al., 2011) found that large trees are less effective than shrubs and climber species in terms of PM dry deposition. On the other hand, Chen et al. (Chen et al., 2015) quantified the PM deposited by different species of trees, shrubs and lianas located in an urban green space in Beijing, China. In this case, the maximum dry deposition of $PM_{2.5}$ for trees, shrubs and lianas was 70 $\mu g \cdot cm^{-2} \cdot day^{-1}$, 40 $\mu g \cdot cm^{-2}$·day-1and 25 $\mu g \cdot cm^{-2} \cdot day^{-1}$, respectively. In Santiago, Chile, Muñoz et al. (D. Muñoz et al., 2017) concluded that roadside trees are effective in reducing air pollution by capturing PM as they act as passive collectors of PM. Furthermore, they found a positive correlation between the particles deposited on the leaves of *Platanus orientalis* and the traffic flows, which evidences that dry deposition of PM is significantly influenced by PM concentration close to the vegetation. Similar results were reported by Przybysz et al. (Przybysz et al., 2014) and Ottelé et al. (Ottel et al., 2010a) that studied other species.

Regarding the impact of the species used in GRs and GWs, Table 2-1 presents a summary of the most recent experimental research about the potential of GRs and GWs to mitigate air pollution, where different species of shrubs, grasses, herbaceous plants, climbers and lianas species have been studied. Table 2-1 shows that few studies on quantifying such potential have been carried out. First, two main approaches to evaluate that effect are reported in the literature: (1) measuring the dry deposition of PM on GRs and GWs vegetation and (2) estimating the reduction of PM concentration due to GRs and GWs vegetation. While dry deposition is measured by the gravimetric method (Chen et al., 2015; Dzierżanowski et al., 2011; Przybysz et al., 2014; Speak et al., 2012a), the impact of GRs and GWs on PM concentration is mostly measured in environmental chambers (Papaioannou, 2013; Stapleton & Ruiz-Rudolph, 2016). An exception is the study of Tan and Sia (Tan & Sia, 2005), who measured the impact of GRs on outdoor PM concentration. Besides, it is difficult to compare the results shown on Table 2-1 because they report dry deposition of PM during different measurement periods in urban areas with different ambient PM concentrations. For example, the measuring period in Speak et al. (Speak et al., 2012a) was two years while it was just one month in Chen et al. (Chen et al., 2015). Nonetheless, the differences in the results reported in Table 2-1 suggests that some species are more efficient in mitigating PM pollution. Speak et al. (Speak et al., 2012a) have explained those differences by variability in the species' morphology. Chen et al. . (Chen et al., 2015) pointed out that the difference between the effectiveness as bio-filter of PM of each species could be associated with the layout configuration (relative location among species) in the environment where they develop.

Given the limited space to plant new trees and large shrubs in dense cities, the GRs and GWs have been identified as valuable strategies that, in addition of promoting building energy savings, reducing heat island effect, controlling water run-off and promoting biodiversity, provide room for improving urban air quality (Berardi et al., 2014). However, most of country/municipality's public policies that either promote or regulate the incorporation of GRs and GWs in buildings are focused on building energy savings, stormwater runoff management and biodiversity. Since 2010, the City of Copenhagen, Denmark, has incorporated the mandatory implementation of green roofs in local plans for rainwater runoff control. There are also plans to cover the old roofs of the city with vegetation in order to achieve a carbon neutral built environment by 2025. On the other and, the city of Buenos Aires, Argentina, established the Law 4428 of GRs and Terraces that regulates the incorporation of GRs in buildings but it is not mandatory, yet (López, 2016). Currently, few cities or countries have established policies that promote GRs and

GWs to mitigate air pollution such as Chicago (Frith & Gedg, 2016; Gonzalez, 2015) and France (Frith & Gedg, 2016). France has recently instituted a law with the goal of returning nature to the city so that new commercial buildings integrate GRs or photovoltaic panels to reduce atmospheric pollution by PM (Frith & Gedg, 2016).

To support public policies for implementation of GRs and GWs to mitigate urban air pollution, it is necessary to demonstrate the environmental benefits of different local species to encourage their use (Berardi et al., 2014), identify the species or set of species that maximize dry deposition of PM on their leaves (Papaioannou, 2013; Perini, Ottelé, Giulini, Magliocco, & Roccotiello, 2017), make comparisons and generate design recommendations (X. Zhang, Shen, Tam, & Lee, 2012b). Nevertheless, the quantification of PM dry deposition potential depends on multiple factors that affect each species in the environment, such as plant species, structure of the vegetation, exposure level to PM, location and microclimatic conditions, among others (Ottel et al., 2010a).

The state-of-the-art shows that, despite the potential impact of GRs and GWs on mitigation of urban air pollution, there is little information on the quantification of PM deposited among species typically used in GRs and GWs. In different urban areas, several species are currently used but very few have been studied from that standpoint. This is crucial information to support design criteria of GRs and GWs to maximize their environmental benefits, the development of public policies and inclusion of GRs and GWs in urban planning. Therefore, the aim of this study is to quantify the dry deposition of PM_{10} and $PM_{2.5}$ of nine vegetation species mostly used in GRs and GWs in semiarid climates of Chile, and to identify which species would be more efficient in removing urban atmospheric pollution by MP_{10} and $MP_{2.5}$.

Table 2-1 Summary of the most recent experimental research on the potential of GRs and GWs to capture PM

Ref.	Type of infrastructure	Method	Type vegetation	Location	Species studied	Findings	Potential for air remediation
(Speak et al., 2012a)	GRs	Scanning Electron Microscopy (SEM)	Grasses and herbaceous plants	Manchester, UK	*Agrostis stolonifera, Festuca rubra, Plantago lanceolata and Sedum Album*	Overall, GRS were not as efficient as the trees. However, *Festuca rubra* showed a potential for air pollution mitigation closes to trees.	Dry deposition of PM_{10} between 0.42 g・m^{-2}・year^{-1} and 1.81 g・m^{-2}・year^{-1}.
(Papaioannou, 2013)	GWs	PM concentration monitoring in an environmental chamber	Grasses	California, USA	*Festuca festina*	GWs must function as air PM filters in indoor spaces	PM_{10} concentration is reduced between 20% and 40%
(Tan & Sia, 2005)	GRs	Outdoor PM concentration monitoring	Shrubs, grasses and herbaceous plants	Singapore	*Furcraea foetida 'Mediopicta', Aloe vera Aptenia Cordifolia, Carpobrutus edulis, Delosperma lineare, Zephyranthes candida, Zephyranthes rosea, Lonicera japonica, Callisia repens, Tradescantia pallida 'Purpurea', Sanseveria trifasciata 'Hahnii', Sanseveria trifasciata 'Golden Hahnii', Sanseveria trifasciata 'Laurentii', Liriope muscari, Kelanchoe tomentosa, Sedum acre, Sedum mexicanum, Sedum nussbaumerianum, Sedum sarmentosum, Sedum sexangulare, Ophiopogon intermedius, Aglaia odorata, Pandanus amaryllifolius, Portulaca grandiflora cultivars, Ixora coccinea* and *Murraya paniculata*	The GRs reduces the level of PM caused by traffic emissions	Up to 6% of PM_{10} is removed in the study area
(Dzierżanowski et al., 2011)	Trees, GRs and GWs	Gravimetric method	Trees, shrubs and climbers	Nowoursynowska, Poland	Trees: *A. campestre, F. excelsior, P. hispanica* and *T. cordata* GRs: *Forsythia×intermedia Zabel, Physocarpus opulifolius (L.) Maxim.* and *Spiraea japonica L* GWs: *Hedera helix L.*	There are significant differences between species. The shrub and climber species were more efficient than the trees studied	Dry deposition of total PM between 18 µg・cm^{-2} and 25 µg・cm^{-2} for two growing seasons

(Przybysz et al., 2014)	Trees and GWs	Gravimetric method	Trees and climber	Warsaw, Poland	Trees: : *T. baccata* and *P. sylvestris* GWs: *Hedera helix L.*	The species studied accumulated large quantities of PM. *H. helix L.* was less efficient. The evergreen plants are efficient in collecting PM on their foliage.	Dry deposition of total PM between 8 µg・cm^{-2} and 140,6 µg・cm^{-2} for month
(Stapleton & Ruiz-Rudolph, 2016)	Indoor specie s	PM concentration monitoring in an environment al chamber	Shrubs	Santiago, Chile	*Chamaedorea elegans, Peperomia jayde, Chlorophytum comosum 'variegatum' (spider plant), Dracaena deremensis Janet Craig' compacta, Ficus benjamina, Dracaena marginata, Schefflera arboricola 'Variegata', Juniperus chinensis 'San Jose', Sansevieria trifasciata, Sophora macrocarpa 'mayo'* and *Quercus suber*	Shrubs can reduce the environmental pollution of ultrafine particles in indoor environments, and there are more effective species than others.	Reduce up to 5,9% of indoor $PM_{2.5}$ concentration
(Chen et al., 2015)	Trees, GRs and GWs	Gravimetric method	Trees, shrubs and lianas	Beijing, China	Trees: 28 species*: Ulmus pumila, Catalpa speciosa, Magnolia denudate, etc.* GRs: *Syringa microphilla, Iles chinesis, Lonicera maackii* and *Sobaria sorbifolia,* GWs: *Parthenoccisus tricuspidata, Campsis grandiflora* and *Parthenoccisus quinquefolia*	There are significant differences on $PM_{2.5}$ dry deposition among species. The layout of species significantly impacts the dry deposition.	Dry deposition of $PM_{2.5}$ between 6 µg・cm^{-2}・day^{-1} and 70 µg・cm^{-2}・day^{-1}
(Perini et al., 2017)	GWs	Scanning Electron Microscopy (SEM)	Shrubs and climber		*Trachelospermum jasminoides, Hedera hélix, Cistus 'Jessamy Beauty'* and *Phlomis fruticosa*	There are significant differences between species. This study showed that sampling season and timing has no influence on the results.	*T. jasminoides* collects a higher number of particles
(Pettit, Irga, Abdo, & Torpy, 2017)	GWs	Biofilter an environment al chamber	Shrubs and climber		*Chlorophytum orchidastrum, Ficus lyrata, Nematanthus glabra, Nephrolepis cordifolia duffii, Nephropelis exaltata bostoniensis, Schefflera amate* and *Schefflera arboricola*	There are significant differences between species associated principally to botanical component.	*N. exaltata b.* outperformed the other species by a significant margin across all PM fractions.

Table 2-2 GRs policies and incentives in the world
(a) Control stormwater runoff (b) Promote biodiversity (c) Building energy savings (d) Promote urban agriculture (e) Reduction of urban heat island effect (f) urban aesthetics (skyrise greening) (g) Generate public amenity spaces (h) Improve air quality.

City or country	Key motivation
Copenhagen (Baykal, 2016)	a, b
Montreal, Canada (Gail, Beth, Hitesh, & Ireen, 2006)	c, d
Toronto, Canada (Gail et al., 2006)	a, e, **h**
Vancouver, Canada (Gail et al., 2006)	a, e, g
Waterloo, Canada (Gail et al., 2006)	a, **h**
Chicago, USA (Gail et al., 2006)	e, h
New York, USA (Gail et al., 2006)	a, e
Portland, USA (Gail et al., 2006)	a
Basel-City, Switzerland	b, c
Münster, Germany (Gail et al., 2006)	a
Singapure (Gail et al., 2006))	f
Stuttgart, Germany (Frith & Gedg, 2016)	**h**
Tokyo, Japan (Gail et al., 2006)	e
France (Frith & Gedg, 2016)	b, c
Buenos Aires, Argentina (López, 2016)	b

2.2. Matters and Methods

2.2.1. Selected Plant Species

Five species (*Pitosporum Tobira, v. n, Lavandula Angustifolia, Lampranthus Spectabillis, Sedum Album* and, *Sedum Reflexum*) were chosen for GRs and four species (*Aptenia cordiflora, Erigeron Karvinskianus, Sedum Palmeri* and*, Sedum Spurium P*.) for GWs. All species were evaluated in terms of their dry deposition of PM_{10} and $PM_{2.5}$ on the leaves and PM captured by the leaf wax. These species were selected because they are the most used in the Metropolitan Region of Chile (Besir & Cuce, 2018; Vera et al., 2014). This region is characterized by a semiarid climate (Bsk) according to the Köppen-Geiger classification (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). The selection criteria were type of species, origin, use, potential of PM dry deposition based on published results (if any) and the preferences of designers and builders about of GRs and GWs vegetation species (Besir & Cuce, 2018; Vera et al., 2014). Some designer decisions about the species used are based on landscaping characteristics, irrigation and maintenance requirement and tolerance to drought. Figure 2-1 shows all species. *P. Tobira, L. Angustifolia* are shrubs, while the rest of species are different alternatives of low growing perennial herbaceous plants. Among them, *S. Album, S. Reflexum, A. Cordiflora, S. Palmeri* and *S. Spurium p*. are succulent species.

Figure 2-1 Nine species of GRs and GWs studied. 1 indicates species used in GRs, 2 indicates the species used in GWs

2.2.2. Experimental Site and Setup

To estimate the dry deposition of PM of each species studied, experiments were performed in a room under controlled environmental conditions. The room is part of the Laboratory of Vegetative Infrastructure of Buildings (LIVE for its acronym in Spanish) at the Pontificia Universidad Católica de Chile. The room has a volume and floor area of 60 m^3 and 25 m^2, respectively, and shows a very low infiltration rate (0.3 ach @ 4Pa). While the room temperature and air humidity were controlled at 20°C and 50%, respectively, by means of an air heating and cooling system, the air speed was 0.4 $m \cdot s^{-1}$. The environment was monitored in the presence of each type of vegetation separately. In order to simulate the presence of vegetation cover inside the module, a surface of 5 m^2 of mockups were installed on the test room floor. The nine species were analyzed in horizontal position considering that in this condition, the picking height should not influence the PM deposition according to the findings of Ottelé et al. (Ottel et al., 2010a).

The plants were obtained from different nurseries around Santiago of Chile (33.44 S, 70.67 W); they were planted in mockups of 0.5x0.5 m^2 and 0.2 m of substrate thickness at LIVE under outdoor conditions. Thus, they were maintained at optimum conditions from January through May 2017. The substrate used was composed of humus, vegetal soil and perlite (Vera et al., 2017). Due to the requirement of PAR radiation by the vegetation, 2.5 $kWh \cdot m^{-2} \cdot day^{-1}$ of radiation was generated inside the test room. Before starting each test, the leaves were washed by spraying distilled water to remove the previously adhered PM that could exist.

The room air was subjected to forced convection with the use of two fans to achieve a well-mixed indoor air. Then, indoor PM was generated by clean combustion (without fire) of 0.34 g of incense for 40 min using a heating plate at 300 °C. Once the combustion was finished, the decay curve of the concentration of PM_{10} and $PM_{2.5}$ in the room was monitored for 3 h. The maximum concentration levels of PM_{10} and $PM_{2.5}$ reached inside the test room were 140.3 $\mu g \cdot m^{-3}$ and 139.2 $\mu g \cdot m^{-3}$, respectively, similar to those that happen in air pollution episode during winter season in Santiago (MMA, 2017).

During the experiment, indoor concentrations of PM_{10} and $PM_{2.5}$ were monitored with two Air Quality Particulate Monitors (E-Sampler, Met One, US); air temperature and relative humidity were measured with one meter HMP60 (Vaisala, US); and air speed was monitored above the canopy level with two Davis cup anemometers. Figure 2-2 shows the experimental setup of the test room. The concentrations of PM were measured as 30 s averages. To measure the PM deposited, two runs of the test were carried out; for each run, three random leaf samples of 150 cm^2 each were taken for each species (n = 6) to be processed later with the washing method described in section 2.2.3.

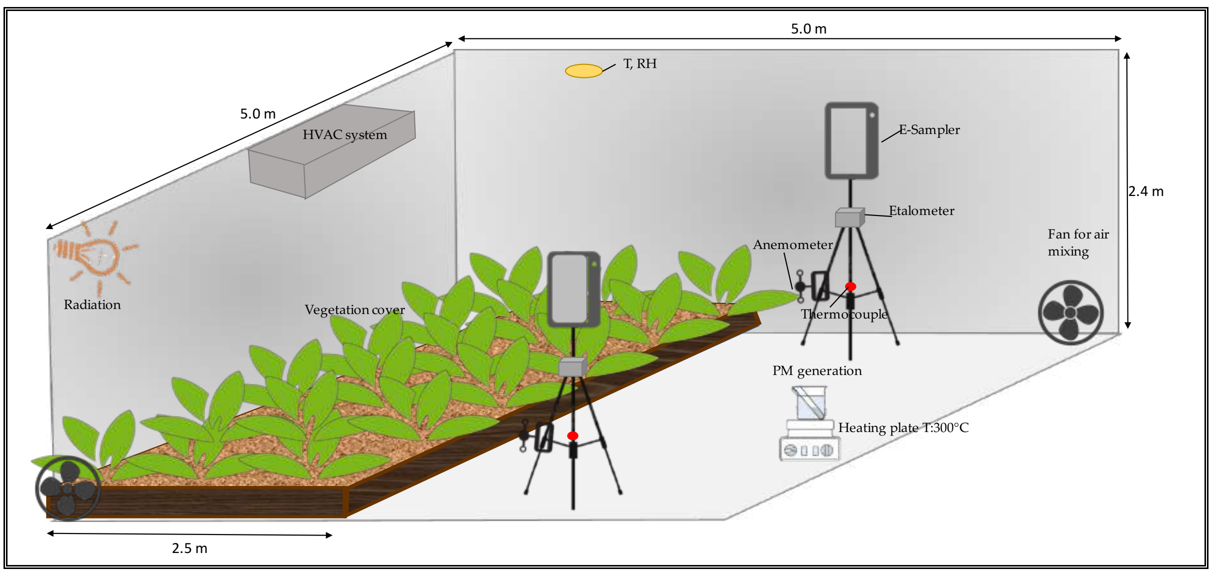


Figure 2-2 Schematic drawing of the test room to evaluate the PM deposition of GRs and GWs species

Moreover, an additional test without vegetation in the test room was carried out. Since the experiments with and without vegetation run under the same conditions, comparing the PM concentration decay curve with and without vegetation estimates the impact of vegetation on PM concentration.

2.2.3. Experimental Method to Quantify the Dry Deposition of PM

The experimental method to quantify the dry deposition of PM of GRs and GWs vegetation species was based on the methodology developed by Dzierżanowski et al. (Dzierżanowski et al., 2011), which was adapted and updated in this research. After exposing GRs and GWs species to the laboratory conditions described in section 2.2.2, samples were processed for the quantification of PM deposited. Initially, three random leaf samples of 150 cm^2 were obtained for each test. Leaves were packaged in sealed bags and transported to a Laboratory of the Faculty of Chemistry at Pontificia Universidad Católica de Chile, were the leaf samples and filters are processed inside of a laminar flow chamber (Intelligent Model Cat. ZHJH-C1112, Labwit Australia) to prevent dust contamination. Sampled leaves were washed with 250 ml deionized water for 5 min and shaken for 1 minute with a vortex stirrer (3000 rpm). The resulting extract was filtered using a N°200 metal screen, then vacuum filtered with 10 µm, 2.5 µm and 0.2 µm pore size filters using Wahtman filter papers grade 91 and grade 42 (Merck, Chile) and ester cellulose filters 0.22 µm (Merck, Chile), respectively. Therefore, three particles size fractions were obtained in each case: large (10-74 µm, coarse (2.5-10 µm) and fine (0.2-2.5 µm). Clean filters were pre-weighed in a microbalance of 1 µg resolution (Sartorius, model Cubis-DF LSM011, Germany) after being dried for 60 min at 40°C and then kept in a desiccator to attain room temperature. The same protocol was used to weigh the mass of each PM size fraction in each filter after filtration stage.

For the quantification of PM deposited on the leaves' wax, samples were washed with 150 ml of chloroform, shaken for 40 seconds with a vortex stirrer (3000 rpm) and filtered using the same filtration procedure as above, but using 0.2 μm PTFE filters (Sartouris, Germany), obtaining particles between 0.2 and 74 μm. Finally, PTFE filters were weighed after 60 min of drying at 40°C. Since dry deposition of PM is usually expressed per surface of the sampled leaves, pictures of the leaf samples were processed with an image processing software (Photoshop®) to determine their Surface.

2.2.4. Quantification of PM Dry Deposition

To estimate PM dry deposition, weights of the filters before and after the filtration process were used, thus the PM retained for each PM size fraction was determined by difference of weighs in each sample as follows:

$$W_{PM} = W_f - W_i \tag{1}$$

where, W_{PM} is the quantity of PM of each sample retained for each fraction of particles (μg); W_f is the final weight after filtering (μg); and W_i is the initial weight of filters (μg). Results are reported as $PM_{2.5}$, PM_{10} and PM in the leaves' wax. The first correspond to fine particles, the second is the sum of fine and course particles, and the third stands for all size particles captured in the leaf wax.

To have an indicator of PM dry deposition, the results are expressed as a function of leaf surfaces and time of exposure to PM as follows:

$$PM_{dd} = W_{PM} \times S_{dd}^{-1} \times t^{-1} \tag{2}$$

where, PM_{dd} is the dry deposition of PM on the leaf surfaces for hour [$\mu g \cdot cm^{-2} \cdot h^{-1}$]; S_{dd} is the surface of leaves where PM is deposited [cm^2]; and t is the time during PM dry deposition occurs [hour].

To calculate the total PM dry deposition, an average of the sum of coarse, fine and wax PM was made for each species and sample. Data were subjected to one-way analysis of variance ANOVA after the normality testing of data using the Shapiro-Wilk Test, which is appropriate for small samples. The significance of differences between mean values was tested using Tukey's Test, a value $p < 0.05$ was considered significant. The tests were made using Microsoft Excel (Microsoft Corp., USA). Values shown on bar charts are means ± standard error (SE) with $n = 6$, which indicates the variability in the measurements.

2.3. Results and Analysis

The results presented in this study are relevant for the mitigation of air pollution in cities of central Chile with serious air pollution levels. Although the vegetation considered in this study has shown good biophysical performance under semiarid climate conditions (Vera et al., 2014), it presents the challenges of balancing maintenance and irrigation requirements and the ability of capturing PM without affecting photosynthesis and transpiration rates (Przybysz et al., 2014).

This section shows the results and analysis of PM deposited on the surface of the leaves according to the methodology described above. Also, this section compares the decay curves of the PM concentration with and without vegetation to evidence the impact generated by vegetation on removing PM.

2.3.1. Dry Deposition of PM of GRs and GWs Species

Figures 2-3 and 2-4 show dry deposition of $PM_{2.5}$ and PM_{10}, respectively, while Figure 2-5 displays PM captured in the wax of the leaves. Shown results in these figures correspond to the mean value and the bars show the standard error (SE). Bars marked with different letters (a, ab, b) stand for significantly different results ($p < 0.05$).

Dry deposited $PM_{2.5}$ ranged from 0.09 $\mu g \cdot cm^{-2} \cdot h^{-1}$ for *S. Spurium P* to 1.32 $\mu g \cdot cm^{-2} \cdot h^{-1}$ for *S. Album*. Figure 2-3 shows three groups of species with high (a), medium (ab) and low capture (b) of PM. The first group (a) is composed only by *S. Album*; the second group (ab) consists of *S. Reflexum, L. Spectabilis, S. Palmeri* and *L. Angustifolia* (ab); and finally, *A. Cordiflora*, *P. Tobira*, *E. Karvinskianus* and *S. Spurium P* conform group (b).

Dry deposition of PM_{10} varied between 0.48 $\mu g \cdot cm^{-2} \cdot h^{-1}$ and 4.70 $\mu g \cdot cm^{-2} \cdot h^{-1}$ for *P. Tobira* and *L. Spectabillis*, respectively (Figure 2-4). For $PM_{2.5}$, three groups of species show significant differences of $PM_{2,5}$ dry deposition. Now *L. Spectabilis* and *S. Album* are part of group (a). The dry deposition values of PM_{10} are higher than those found in literature for the same or similar species. For example, Speak et al. (Speak et al., 2012a) reported values of 0.88 and 0.12 $\mu g \cdot cm^{-2} \cdot day^{-1}$ for *F. Rubra* and *S. Album*, respectively. Values of this study and our study are not directly comparable because testing conditions and measurement technologies are different. For example, Speak et al. (Speak et al., 2012a) exposed GRs vegetation to outdoor conditions in a roof of the city of Manchester (UK), while our study correspond to higher indoor concentrations under very well controlled experimental conditions; also, Speak et al. (Speak et al., 2012a) estimated the capture of PM using a scanning electron microscopy, whereas this research used the gravimetric method.

Regarding PM dry deposition on the leaves' wax, values vary between 0.41 μg·cm^{-2}·h^{-1} for *P. Tobira* and 25.62 μg·cm^{-2}·h^{-1} for *S. Album* (Figure 2-5). These values are higher than others reported for outdoor conditions: 8.7 – 45.2 μg·cm^{-2}·month^{-1} for *H. Hélix*. Once again, three species groups have high, medium and low PM capture potential.

It is noteworthy that most species consistently show the same relative level (high, medium, low) of dry deposition for $PM_{2.5}$. PM_{10} and PM in wax. *S. Album* shows the highest PM dry deposition (group a), *S. Reflexum* and *S. Palmeri* show medium level (group ab) and *P. Tobira*, *E. Karvinskianus* and *S. Spurium P.* show the lowest potential to capture PM (group b). This fact is crucial to choose the most appropriate GRs and GWs vegetation species for mitigating air pollution because of their effectiveness to remove different sizes of PM.

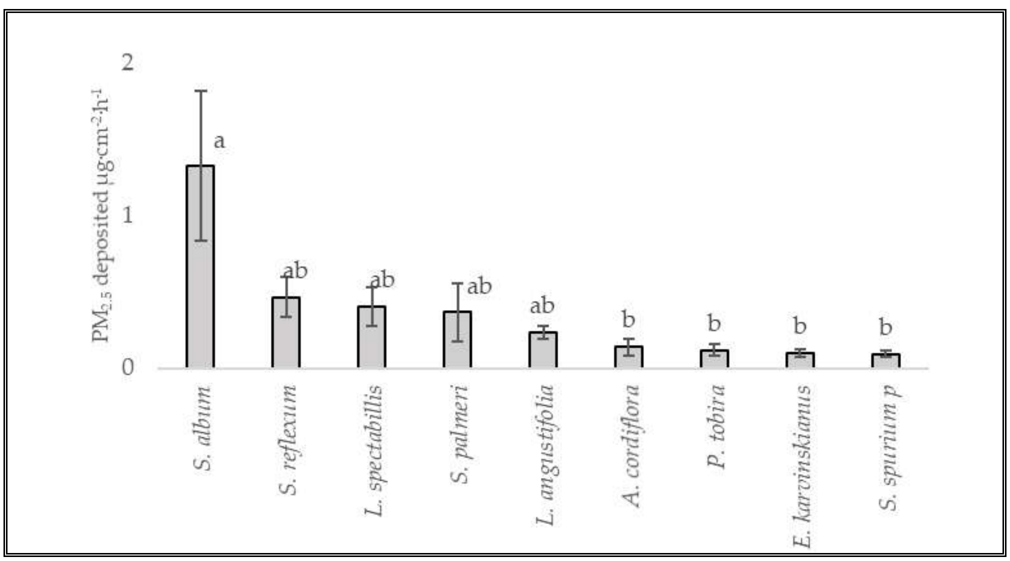


Figure 2-3 $PM_{2.5}$ deposited on the leaves of five species used for GRs and four species used for GWs.
Values shown on bar charts are means ± SE (standard error), n = 6.

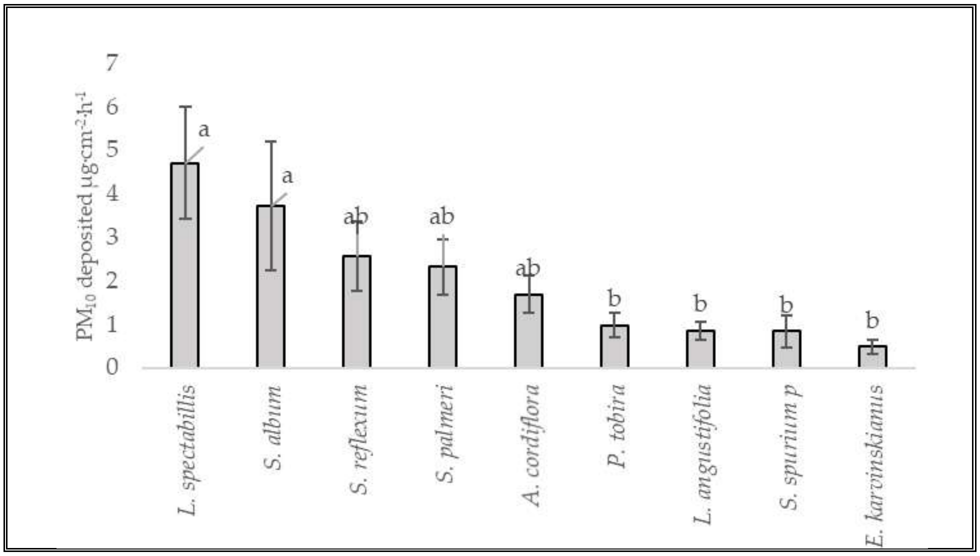


Figure 2-4 PM_{10} deposited on the leaves of five species used for GRs and four species used for GWs.
Values shown on bar charts are means ± SE (standard error), n = 6.

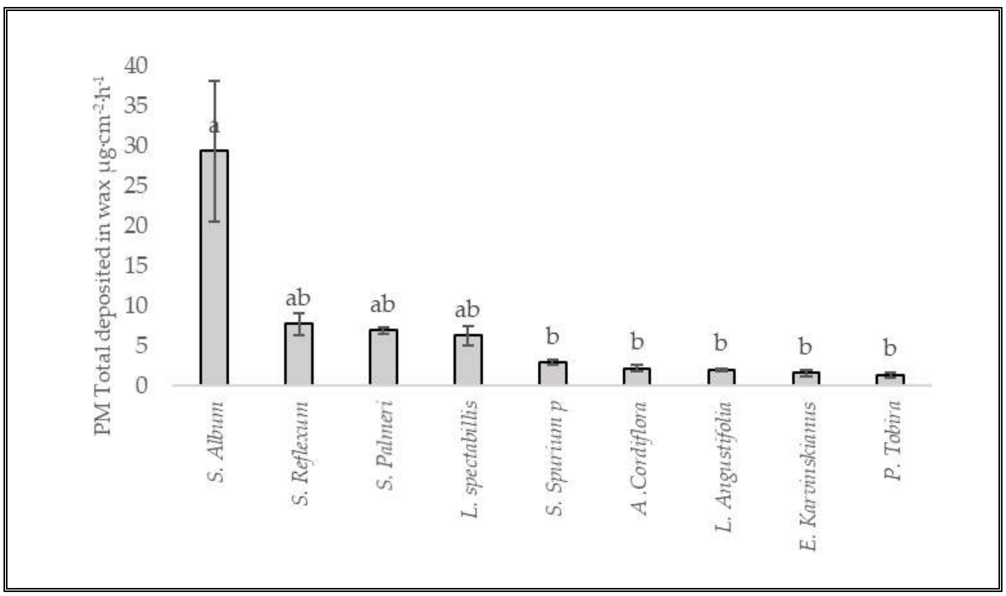


Figure 2-5 PM deposited in the wax of the leaves of five species used for GRs and four species used for GWs.
Values shown on bar charts are means ± SE (standard error), n = 6

Table 2-3 presents the total amount of PM deposited on the species of GRs and GWs, which corresponds to the average of total PM calculated for each sample. The large variation among the experimental results obtained in this study highlights the need of evaluating PM dry deposition potential across GRs and GWs species. Our results show 52% of the PM deposited on the leaves were particles fixed in wax. For the case of S *album*, this value was 84%, being the most efficient species studied. This percentage is comparable to the PM captured by wax in trees reported by (Dzierżanowski et al., 2011; Sæbø et al., 2012) was up to 83%. Leaf wax captures larger amounts of PM than that just deposited on the leaves. Deposited PM on the leaves can be resuspended (Song et al., 2015) by turbulence and stronger winds and might be washed by rain. Nevertheless, PM deposited on wax ends being captured by the leaves.

Figure 2-6 shows that leaf wax is far more efficient in capturing PM than the PM merely deposited on the leaves' surface but not attached to wax —quantified by washing leaves with water — the latter is likely the inorganic PM fraction, like suspended soil dust, for instance. In other words, the organic fraction of PM is more efficiently captured by leaves' wax. However, the methodology used in this research does not allowed us to distinguish if the PM captured in the wax is fine or coarse neither its chemical speciation. Similarly, it was not possible to quantify the soluble particulate matter in water and in chloroform, which is considered an important fraction of ultrafine particles. In this study, the potential of vegetation simulating critical air quality conditions was analyzed in an environmental chamber; therefore, the results of this study could be compared with tests subjected to real environmental conditions as future research.

Table 2-3 The total amount of PM deposited for five species used in GRs and four in GWs.

Specie	PM Total deposited

	($\mu g \cdot cm^{-2} \cdot h^{-1}$)	
	Mean	SD
S. Album	29.33	8.74
S. Reflexum	7.77	1.34
S. Palmeri	6.93	0.42
L. Spectabillis	6.28	1.16
S. Spurium P	2.93	0.32
A. Cordiflora	2.20	0.44
L. Angustifolia	1.98	0.16
E. Karvinskianus	1.62	0.42
P. Tobira	1.38	0.32

2.3.2. Effects of Vegetation on PM Concentration

Figure 2-6 shows a comparison between the decay curves of the $PM_{2.5}$ and PM_{10} concentrations in the test room with and without vegetation under laboratory conditions for three species. *S. Album* is the species evaluated that shows the highest PM dry deposition by the leaf washing/gravimetric method (Figures 2-6a and 2-6b), *L. Angustifolia* shows the intermedium values (Figures 2-6c and 2-6d) while *S. Spurium P* presented the lowest levels of PM dry deposition using the same method (Figures 2-6e and 2-6f). The difference between the decay curves with and without vegetation (gray zone) reflects the impact of vegetation on reducing the concentration of PM in the environment.

Comparing the decay curves of PM, the impact of vegetation on the PM concentrations is significant. The tests with vegetation show lower PM peaks and the decay curves for all GRs and GWs vegetation species tested (some are not shown here due to manuscript length limitations). A similar effect was found by Papaioannou (Papaioannou, 2013), who reported a decrease of 27.7% of the total ultrafine particles by monitoring the concentration of PM with vegetation for GWs installed in an environmental chamber. Moreover, the decay curves of PM showed that for all cases, the deposition of particles inside the room increased with the presence of vegetation and indicates that some species can have better performance than others in terms of PM removed from the environment. In this case, Figure 2-6 shows that *S. Album* is more effective in lowering $PM_{2.5}$ and PM_{10} than the case of *L. Angustifolia* and *S. Spurium P.*

The difference in the results of deposited PM among species can be caused by variations of environmental factors (Ottel et al., 2010a), leaf surface (Beckett, Freer Smith, & Taylor, 2000; Hwang, Yook, & Ahn, 2011), and leaf anatomical traits. Considering that the vegetation was subjected to the same environmental conditions (e.g.: air temperature, relative humidity and speed, PM concentrations), these factors do not influence the results. Although some findings in trees relate the differences in PM deposition among species with the leaf surface (Beckett et al., 2000; Hwang et al., 2011), such relationship was not found in this study. However, the state-of-the-art shows that smaller leaves have a greater potential for PM capture (Freer-Smith, Beckett, & Taylor, 2005; Leonard, McArthur, & Hochuli, 2016). This effect is known as edge effect, which is greater in smaller leaves due to their high perimeter/surface area ratio (Weerakkody, Dover, Mitchell, & Reiling, 2018). In our research, species with smaller leaves (e.g.: *S. Album*, *L. Spectabilis*, *S. Reflexum*) were found to have the highest PM dry deposition. Moreover, the differences in deposited PM found among species are also probably related to the differences of leaves anatomical traits among species, such as the presence of trichomes and hair, leaf roughness, and stomata number and size. In fact, the literature review shows that a higher leaf roughness and the presence of hair and trichomes increase the PM capture potential of trees (Beckett et al., 2000; Hwang et al., 2011; Song et al., 2015) and GRs/GWs vegetation (Burkhardt, 2010; Ottel et al., 2010a; Perini et al., 2017; Speak et al., 2012a). Although this paper is not focused on evaluating the effect of these leaf anatomical characteristics on PM capture potential, some not conclusive evidence about this effect was obtained from scanning electron microscope (SEM) images. *S. Album* has high leaf roughness (Figure 2-7a), the presence of trichomes and the highest values of PM dry deposition (group a). On the other hand, *P. Tobira* has very smooth leaves (Figure 2-7b), lack of trichomes, and very low PM dry deposition (group b).

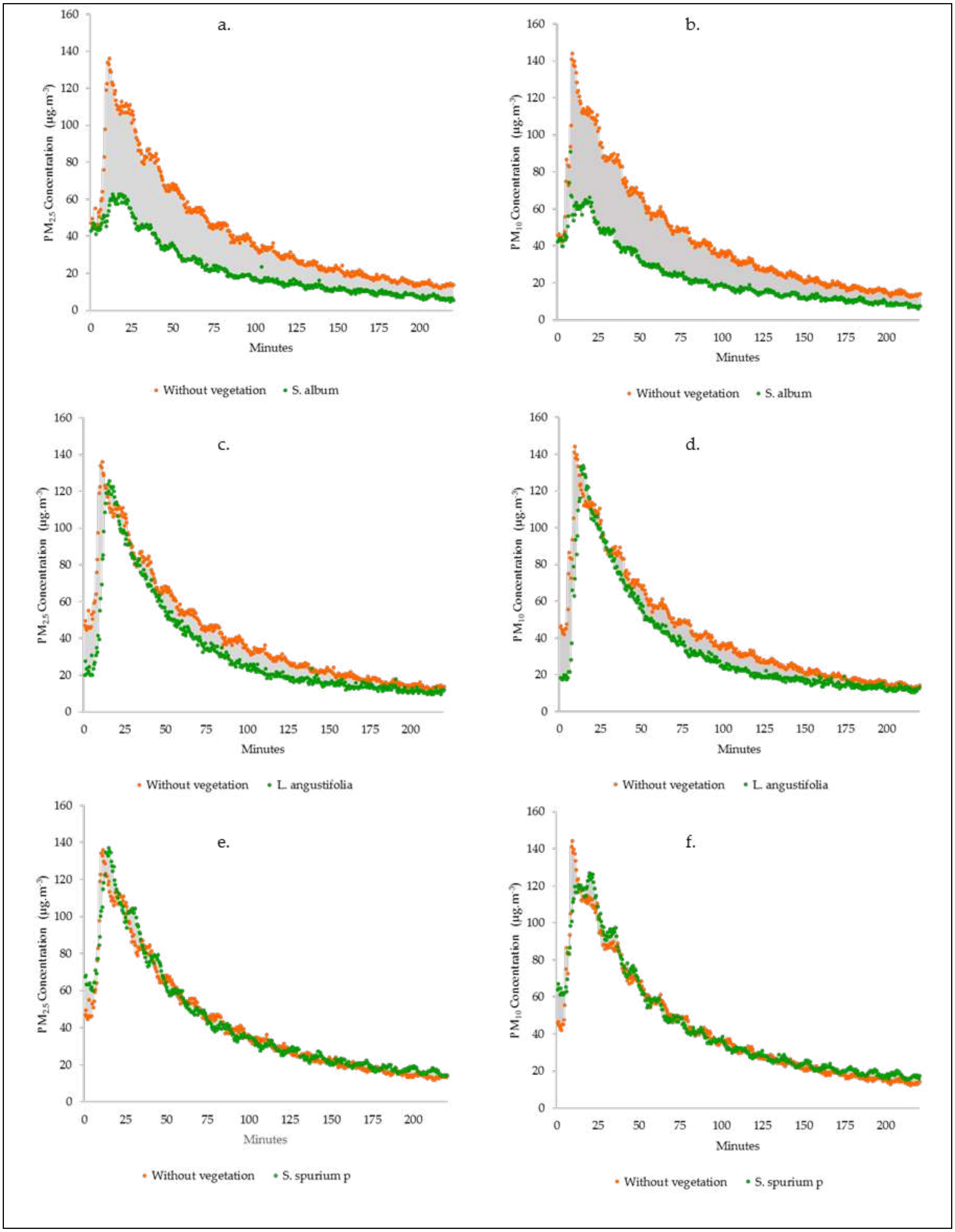
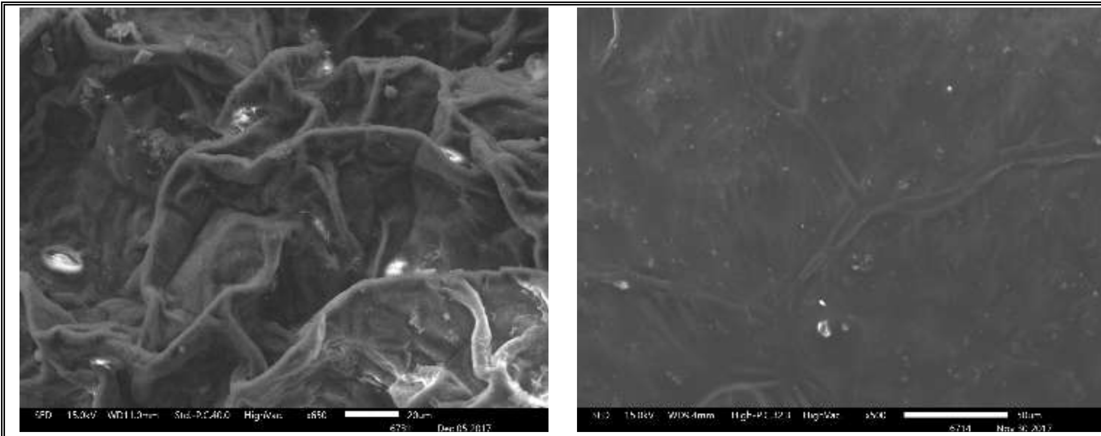


Figure 2-6 $PM_{2.5}$ and PM_{10} concentrations with and without vegetation for *S. Album* (a and b), *L. Angustifolia* (c and d) and *S. Spurium P* (e and f).



(a) (b)

Figure 2-7 SEM images showing roughness of: (a) *S. Album* (650×), (b) P. Tobira (500×)

2.3.3. Other Performance Aspects to be Considered

Regarding the selection of a species to be installed in a GRs or GWs, it is necessary to consider other criteria such as irrigation and maintenance requirements and resistance to drought and lower temperatures, which are performance aspects of GRs and GWs that strongly impact the survival of the vegetation used. For instance, *E. karvinskianus* and *A. cordiflora* presented leaf deterioration after the tests and in the presence of low temperatures, unlike the other species that were tested under the same environmental conditions. Therefore, it is important to balance the potential of PM capture with other performance parameters to choose the most proper species to mitigate urban air pollution. For instance, fine PM can enter through stomata (Song et al., 2015) and affect photosynthesis, which can also deteriorate the plant (Freer-Smith et al., 2005; Przybysz et al., 2014).

2.4. Conclusions

GRs and GWs are claimed to cause several benefits to buildings and urban areas such as building energy efficiency, rainwater runoff management, biodiversity, among others. As consequence, several countries and cities have developed public policies to regulate and motivate the implementation of these envelope technologies in buildings. However, improving urban air quality has triggered few country/city regulations to promote GRs and GWs. This might be a result that few studies about the impact of GRs and GWs on urban air pollution have been carried out. Several cities in central Chile suffer severe air pollution problems in winter season, thus GRs and GWs can contribute to mitigate it. Therefore, the main objective of this paper was to quantify the dry deposition of PM ($PM_{2.5}$, PM_{10} and wax) of several vegetation species commonly used in GRs and GWs in semiarid climates. To accomplish this objective, an experimental method was implemented to evaluate the dry deposition of PM of nine species (*P. Tobira, L. Angustifolia, L. Spectabillis, S. Album* and *S. Reflexum* for GRs and *A. Cordiflora, E. KarvinskianusK, S. Palmeri P*and *S. Spurium P.* for GWs), which are the most used in semiarid climates of Central Chile. The main conclusions of this paper are:

- Vegetation of GRs and GWs can significantly reduce the peak and concentrations of $PM_{2.5}$ and PM_{10}. *S. Album* and *S. Reflexum* reduced $PM_{2.5}$ peak concentrations up to 45.3% and 71.4%, of the peak concentrations with no vegetation, respectively. Similar results were found for $PM_{10.}$
- Statistically significant differences of PM dry deposition were found among the GRs and GWs vegetation species studied. Three distinctive groups of species were identifying that shown high, medium and low potential to remove $PM_{2.5}$, PM_{10} and PM in leaf wax. *S. Album* showed the highest total PM dry deposition (29.3 ± 8.7 $\mu g \cdot cm^{-2} \cdot h^{-1}$) while the lowest values were found for *L. Angustifolia, E. Karvinskianus* and *P. Tobira.*

- It was consistently found that species show high, medium or low dry deposition values for $PM_{2.5}$, PM_{10} and wax. These is important because the ability of species to remove PM is not dependent of the PM size and the way (dry deposition on the leaves vs captured by leaf wax) how PM is removed from the environment. This fact simplifies the decision of policy-makers and designers about the species that can have higher impact on reducing urban air pollution.

The results of this paper demonstrate that vegetation of GRs and GWs can remove a significant amount of PM from polluted air, thus these technologies can contribute to mitigate air pollution in urban environments. Moreover, this paper illustrates that this potential of removing PM varies significantly among different vegetation species commonly used in GRs and GWs in semiarid regions. As a consequence, species of GRs and GWs needs to be carefully chosen to maximize the impact of GRs and GWs on mitigation urban air pollution. Moreover, the results shown in this paper can sustain public policies that regulate and promote the implementation of these envelope technologies in buildings.

2.5. Acknowledgments

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3. Effects of Biodiversity in Green Roofs and Walls on the Capture of Fine Particulate Matter

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Abstract:

Exposure to ambient $PM_{2.5}$ poses serious threats to human health. In such cases, the presence of green roofs (GRs) and green walls (GWs) has several environmental benefits, including the capture of the pollutant. Choosing appropriate designs of [1]GWs and GRs to improve urban air quality is challenging because their performances depend on their constituent species and environmental characteristics of the particular locality. Capture of $PM_{2.5}$ by different plant species of GRs and GWs has been measured only on monocultures. The impact of planting different species together (polycultures) on capturing $PM_{2.5}$ remains unexplored. This paper aims to evaluate the impact of biodiverse GRs and GWs on $PM_{2.5}$ capture. Seven species were analyzed as polycultures: *S. album, Lampranthus spectabillis, Sedum spurium P, Lavandula angustifolia, Erigeron karvinskianus, Aptenia cordifolia, and Sedum palmeri.* $PM_{2.5}$ capture was measured by two methods: gravimetric determination and decay curve. Gravimetric results suggest that higher the biodiversity of plants in GRs and GWs, higher the $PM_{2.5}$ capture, particularly for species with relatively low capture when used as monocultures. The ability of different to capture $PM_{2.5}$ is dependent on the plant species, relative position of plants within the polyculture, and horizontal (GRs) or vertical (GWs) layout. Decay method results suggest

[1]GWs: Green walls, [2]GRs: Green roofs, [3]GI: Green infrastructures, [4]ANOVA: One-way analysis of variance

that polycultures could be more effective in long-term reduction of high $PM_{2.5}$ concentrations

Keywords: air quality, dry deposition, green façades, living walls, polycultures, vegetation species.

3.1. Introduction

Urban air quality is a subject of concern due to its impact on public health worldwide (WHO, 2021). Multiple strategies have been proposed to improve urban air quality, such as monitoring emission standards, air quality management, economic instruments, etc. The use of [3]GI such as trees (Cabaraban, Kroll, Hirabayashi, & Nowak, 2013; Jayasooriya, Ng, Muthukumaran, & Perera, 2017; A. Jeanjean, Buccolieri, Eddy, Monks, & Leigh, 2017), shrubs, hedges (Abhijith et al., 2017; Wania, Bruse, Blond, & Weber, 2012),[2]GRs (Abhijith et al., 2017; Wania et al., 2012; Jun Yang et al., 2008), and [1]GWs (Abhijith et al., 2017; Ottel, van Bohemen, & Fraaij, 2010b; Viecco et al., 2018), has been considered as a strategy to improve urban air quality due to the well-known ability of vegetation to filter pollutants (Weyens et al., 2015). GRs and GWs have been known to mitigate multiple environmental impacts in cities, such as reducing building energy consumption, mitigating urban heat island effect, mitigating floods, and improving air quality (Besir & Cuce, 2018). Several studies have focused on the capture of particulate matter (PM) through dry deposition by some types of vegetation. PM is a type of air pollutant with serious impacts on human health, especially particles with size smaller than 2.5 μm, known as $PM_{2.5}$ (WHO, 2015). These particles are capable of entering the human respiratory tract and reaching the lungs, and have short, medium and long term health impacts (WHO, 2016a). Long term exposure to ambient $PM_{2.5}$ is associated with the development of multiple cardio-respiratory diseases and lung cancer, leading to millions of premature deaths per year worldwide (Burnett et al., 2018; Chow et al., 2006; Hamanaka & Mutlu, 2018; Pope & Dockery, 2006; WHO, 2016a).

The use of GRs and GWs in cities is feasible due to the presence of buildings with large areas available to accommodate them (Mohajeri, Gudmundsson, & Scartezzini, 2015). However, identifying the appropriate types of vegetation for each environment is challenging considering the typical characteristics of different species and the climatic conditions required for their development (Dunnett, Nagase, Booth, & Grime, 2008).

Literature review shows a positive impact of monoculture vegetation i.e. a single species in GRs and GWs on air quality. For example, Viecco et al., (2018) and Jun Yang et al., (2008) have highlighted the potential of *Sedum album* to capture $PM_{2.5}$. Viecco et al., (2018) studied nine GRs and GWs designed as monocultures for the capture of $PM_{2.5}$. Table 3-1 presents the results of $PM_{2.5}$ capture by each species, derived from the results reported by Viecco et al., (2018), and expressed as surface mass flux. This data suggests the potential of a variety of plant species to capture PM, emphasizing the need for deeper understanding and evaluation of their potential in order to estimate their impact on mitigating urban air pollution.

However, there is a lack of research on the impact of biodiverse vegetation in GRs and GWs on the capture of $PM_{2.5}$. Several authors suggest that compared to monocultures, biodiversity of plants could improve their ability to provide multiple and effective ecoservices such as temperature regulation, protection of watersheds, pollution uptake, and decreasing weed biomass, among others (Cook-Patton & Bauerle, 2012; Kiær, Skovgaard, & Østergård, 2009; Upadhyaya & Blackshaw, 2007; W. Zhang et al., 2017). A previous study has showed positive interactions between plant biodiversity and ecosystem functions of vegetation (Isbell et al., 2017). Yield stability weed suppression and pest suppression are some of the agroecosystem services provided by biodiversity.

Table 3-1 $PM_{2.5}$ capture of monocultures.
Derived from Viecco et al., (2018)

	$PM_{2.5}$ ($\mu g \cdot cm^{-2} \cdot h^{-1}$)		
Species	**Mean**	**SD**	**Plant type**
S. album	1.32	0.49	Herbaceous
Sedum reflexum	0.47	0.13	Herbaceous
Sedum palmeri	0.36	0.19	Herbaceous
Lampranthus spectabillis	0.40	0.13	Herbaceous
Sedum spurium P	0.09	0.02	Herbaceous
Aptenia cordifolia	0.14	0.05	Herbaceous
Lavandula angustifolia	0.23	0.04	Herbaceous
Erigeron karvinskianus	0.10	0.03	Shrub
Pitosporum tobira, v. n.	0.12	0.04	Shrub

As per a previous study, polycultures could be more efficient than monocultures in enhancing the efficiency of GRs in improving the species ability to survive and its ability to provide valuable services (Lundholm, MacIvor, MacDougall, & Ranalli, 2010). Increased plant productivity could improve rooftop insulation, reflectance, and cooling from evapotranspiration (Alexandri & Jones, 2008; Kumar & Kaushik, 2005; Verheyen et al., 2008). Higher complexity of vegetation could also increase rainwater retention (Dunnett et al., 2008; Rixen & Mulder, 2005). Moreover, biodiversity of plants could reduce the need for fertilizer (Berndtsson, 2010; Bracken & Stachowicz, 2006; Cardinale, 2011), improve the temporal stability of resources, and offer a better environment to sustain animal communities (Brenneisen, 2003; Menz et al., 2011). Additionally, polycultures improve the aesthetic of GRs (Fuller, Irvine, Devine-Wright, Warren, & Gaston, 2007; Nagase & Dunnett, 2010) and GWs.

Therefore, it might be expected that plant biodiversity enhances the PM capture ability of GRs and GWs, and hence, increases their capability of improving urban air quality. This hypothesis is sustained by the fact that biodiversity increases biomass, and hence, the leaves' surface area (Jia Yang, Wang, & Xie, 2015), which in turn would favor a larger capture of PM by dry deposition. This paper aims to understand and evaluate the impact of plant biodiversity on the performance of GRs and GWs in $PM_{2.5}$ capture. Results of this study can be used to design GRs and GWs with appropriate vegetation for urban planning and supporting the development of public policies for greening cities.

3.2. Materials and Methods

The two methods of measuring PM capture explained in the section 'Methods of measuring $PM_{2.5}$ capture', were used to compare the capture of $PM_{2.5}$ by monoculture and polyculture vegetation in GRs and GWs. Gravimetric analysis method was used to determine the effect of biodiversity on the $PM_{2.5}$ capture potential of each species, while decay curve method was used to determine the synergistic effect of biodiversity, using continuous measurements. This section details the experimental design and research methodology.

3.2.1. Methods of Measuring $PM_{2.5}$ Capture

a. Gravimetric analysis method

This method consisted of gravimetric determination of particles filtered from the liquid with which leaf samples were washed after exposure to ambient PM for a known period. The procedure developed by Dzierżanowski et al. (2011) (Dzierżanowski, Popek, Gawrońska, Sæbø, & Gawroński, 2011), and adapted and implemented by Viecco et al. (2018) (Viecco et al., 2018) was followed in this study. In this method, sampled leaves were washed with 250 mL deionized water to remove particles deposited on the surface of the leaves. For the quantification of PM deposited on the wax of the leaves, samples were washed with 150 mL of chloroform. After sequential filtration of the washing liquid phase, three sizes of particles were obtained: (1) above 10 µm, (2) between 10 µm and 2.5 µm and (3) below 2.5 µm. The $PM_{2.5}$ capture is presented as a function of the surface flux of deposition (µg cm^{-2} h^{-1}). The leaf samples were photographed, and their surfaces are measured. Further details of this method can be mentioned in detail in Viecco et al., (2018) (Viecco et al., 2018). The gravimetric method provides a single set of data per test, but it has the advantage of analyzing the $PM_{2.5}$ capture ability of each species in a given polyculture.

b. *Decay curve method*

In this method, the vegetation was exposed to a high concentration of $PM_{2.5}$ into a test-module for 3 hours and 40 minutes, during which continuous $PM_{2.5}$ measurement was performed. Well mixed conditions in the air were achieved by mechanical ventilation (Viecco et al., 2018). The experiment was conducted in three time periods: (1) $PM_{2.5}$ generation through clean combustion of incense for 40 minutes, (2) attaining the peak of $PM_{2.5}$ concentration, and (3) decay of $PM_{2.5}$ concentration for 3 hours. During the last phase, $PM_{2.5}$ particles were deposited on all surfaces inside the test module, including the vegetation, and no sources of particles are at play. Consequently, the ambient $PM_{2.5}$ concentration decreased, and since dry deposition of PM is a first order removal process, this leads to an exponential decay of $PM_{2.5}$ concentration.

This exponential decay behavior was used to analyze the vegetation's $PM_{2.5}$ capture performance inside the module (Coronel-Brizio, Hernández-Montoya, Jiménez-Montaño, & Mora-Forsbach, 2007). $PM_{2.5}$ concentration inside the test modules is given by:

$$C(t) = C(0)e^{-\lambda t} \tag{3-1}$$

where *C(0)* is the $PM_{2.5}$ concentration at the beginning of phase 3, which corresponds to the peak concentration, λ is the decay rate, and *t* is the elapsed time in phase 3.

3.2.2. Study Site and Plant Materials

Seven different herbaceous and shrub species used as vegetation in GRs and GWs were selected for the study based on the results obtained previously by Viecco et al., (2018) (Viecco et al., 2018) in $PM_{2.5}$ capture by monocultures of these species. The species studied were *S. album, L. spectabillis, S. spurium P, L. angustifolia, E. karvinskianus, A. cordifolia,* and *S. palmeri*. They were grown for five months under ideal irrigation and maintenance conditions in the nursery of the Laboratory of Vegetative Infrastructure of Buildings (LIVE for its acronym in Spanish) at the Pontificia Universidad Católica de Chile, which is located in Santiago, Chile (33º44' S, 70º67' W). This city is characterized by a semiarid climate (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006).

The criteria used to select these species were: (1) $PM_{2.5}$ capture per deposition surface as shown in Table 3-1; (2) water needs according to the crop coefficient (Kc) (Mejía, 2007); and (3) maintenance requirement, which includes pruning, growth of weeds and susceptibility to pests. The last criterion was based on the expert judgment of researchers and practitioners. The plants were evaluated against these criteria, with each criterion sub-categorized into three levels, namely low, medium, and high. A weight of 50%, 25%, and

25% was assigned to $PM_{2.5}$ capture, irrigation needs, and maintenance requirements, respectively (Table 3-2).

3.2.3. Design of Monocultures

The species selected for GRs and grown as monocultures were *S. album, L. spectabillis, S. spurium P, L. angustifolia,* and *E. karvinskianus*. These plants were tested as monocultures for GRs; only *S. album* was tested in vertical mockups (GWs) due to laboratory limitations. *S. album* showed the highest $PM_{2.5}$ capture as a monoculture (Table 3-1).

Table 3-2 Criteria for vegetation selection

Factor	**Level**	**Criteria**		**Weight assigned**
$PM_{2.5}$ Capture	L1	Low	3 species of lower capture	50%
	L2	Medium	3 species of intermediate capture	
	L3	High	3 species of highest capture	
Water needs	L1	Low	Kc between 1.00 and 0.81	25%
	L2	Medium	Kc between 0.80 and 0.41	
	L3	High	Kc between 0.40 and 0.20	
Maintenance	L1	Low	Need for pruning, presence of weeds, susceptibility to pests and renewal	25%
	L2	Medium		
	L3	High		

3.2.4. Design of Polyculture Mixes

Based on the criteria presented in Table 3-2, the species with the highest level of $PM_{2.5}$ capture, water needs, and maintenance were selected. *S. album*, *L. spectabillis*, *S. spurium P*, *L. angustifolia*, and *E. karvinskianus* were chosen for GRs mockups. The species selected for GWs were *L. spectabillis*, *A. cordifolia*, *S. album*, *S. spurium P*, and *S. palmeri*. Then, ten three-species mixes were chosen and analyzed as GRs polycultures, while another ten three-species mixes were analyzed as GWs polycultures (see Fig. 1).

These 20 polyculture mixes were planted in mockups of area 0.5 × 0.5 m^2 with substrate thickness of 0.2 m. The substrate was composed of humus, vegetal soil, and perlite in equal parts (Sandoval et al., 2017; Vera et al., 2017).

Each of the three species of a polyculture mix was planted in one-third area of the same mockup. Moreover, to evaluate if the relative location of the species in each mix could influence the capture of $PM_{2.5}$, the species were laid out in different spatial configurations (A, B, and C) as shown in Fig. 3-1. Three sufficiently developed shrubs and twenty-five herbaceous seedlings were planted in each mockup. In total, 60 polycultures were designed: 30 for GRs (10 mixes in 3 A, B and C configurations), and 30 for GWs, following the same criteria.

3.2.5. Description of the Experiment

The polyculture mixes were exposed to the same process used for Viecco et al., (2018) (Viecco et al., 2018), which was implemented for monocultures. The conditions of the experiments are briefly explained below. Fig. 3-2 represents the experimental procedures.

a. Testing conditions

The experiments were carried out in a test-module under controlled indoor conditions as shown in Table 3-3. These conditions aimed to mimic the temperatures and peak $PM_{2.5}$ concentrations that occur during air pollution episodes in fall and winter seasons in Santiago (Barraza, Lambert, Jorquera, Villalobos, & Gallardo Klenner, 2017).

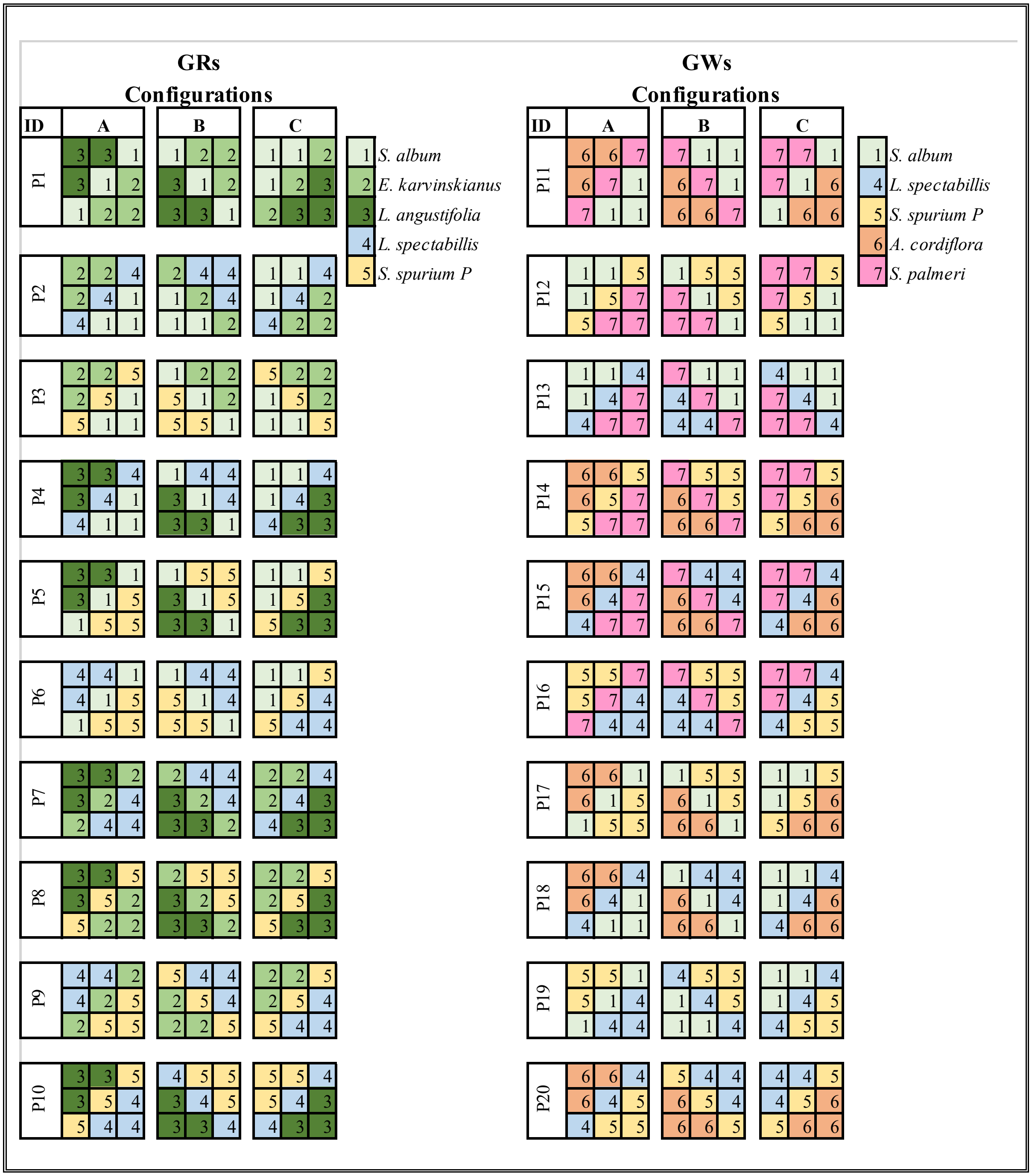

Figure 3-1 Configurations studied for GRs and GWs polycultures. Numbers from 1 to 7 indicate species analyzed. P1 to P10 indicate polycultures for GRs; P11 to P20 for GWs.

Inside the test-module, the polycultures were exposed to high concentrations of $PM_{2.5}$ through incense combustion for 40 minutes. The pollutant was monitored using two air quality particulate monitors (E-Sampler, Met One, Grants Pass, OR, USA) during this period and for 180 minutes after it reached its peak concentration. The method is mentioned in details in Viecco et al., (2018) (Viecco et al., 2018).

The polycultures were placed inside the test-module to be exposed to high concentrations of $PM_{2.5}$. In order to replicate the conditions under which the monocultures were investigated (Viecco et al., 2018), a total vegetation cover of 5 m^2 was considered, that is, 10 mockups were included in each experimental run. Prior to the experiments, the vegetation was planted in each mockup in a horizontal position. However, inside the test-module, the polyculture mixes were placed at two different tilts, 0° and 90°, to represent GRs and GWs, respectively. Before exposing the plants to $PM_{2.5}$ inside the test-module, the leaves were washed with distilled water to remove the PM deposited on them during their stay in the nursery.

For the gravimetric test, the 60 polycultures were subjected to environmental conditions within the test-module as indicated in the section 'Methods of measuring $PM_{2.5}$ capture'. For the decay curve test, the monoculture and polyculture showing the best performance in the gravimetric test were selected.

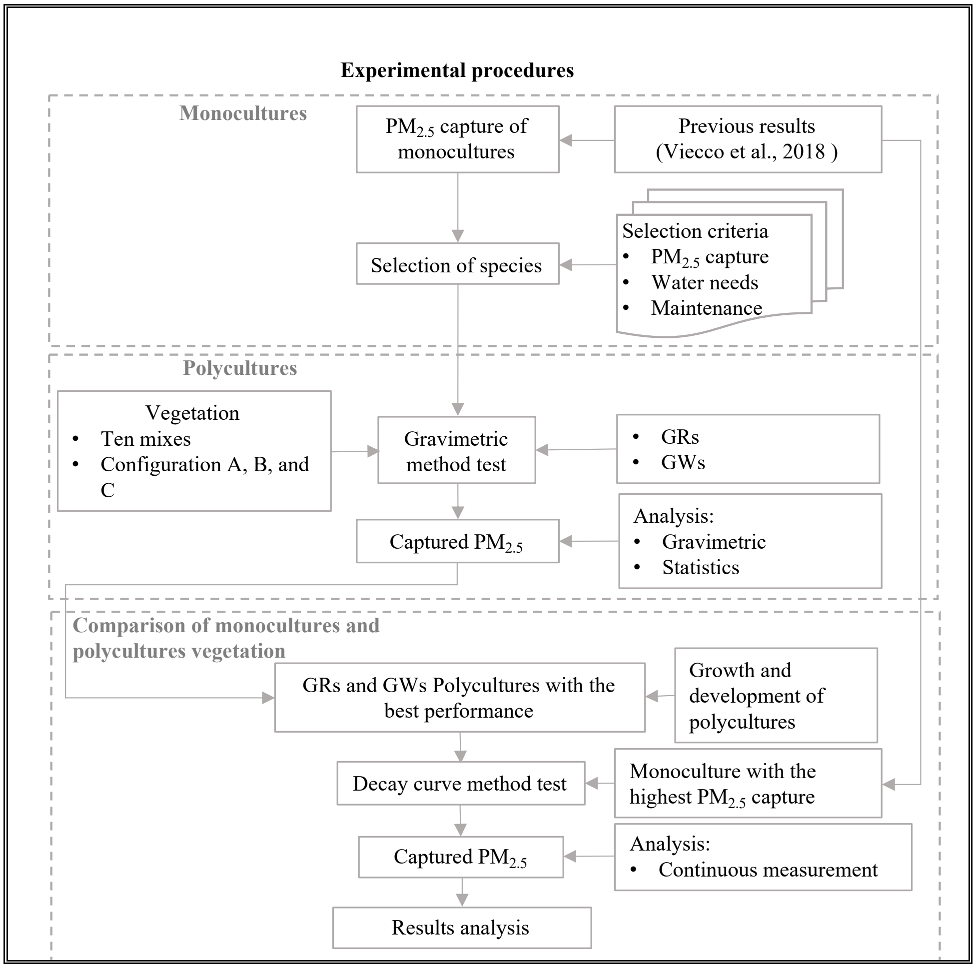

Figure 3-2 Schematic representation of experimental procedures .

Table 3-3 Experimental conditions and characteristics of the test-module.

Description	Set	Measurement equipment
Volume	60 m^3	NA
Floor area	25 m^2	NA
Infiltration rate	0.3 ach @ 4 Pa	Retrotec model q46 automated blower-door. (RETROTEC, USA)
Temperature	20 °C	HMP60 (Vaisala, Grants Pass, OR, USA)
Relative Humidity	50%	
Peak of $PM_{2.5}$ concentration	136.3 μg cm^{-3}	E-Sampler (Met One, Grants Pass, OR, USA)
Air speed	0.4 m s^{-1}	Davis cup anemometers Decagon
Radiation	2.5 kWh m^{-2} day^{-1}	400 W Sodium Light
Vegetation cover	5 m^2	NA
Powdered incense	0.34 g (Combustion temperature: 300 ºC)	Heating plate

3.2.6. Analysis for $PM_{2.5}$ Capture

Gravimetric analysis allows: a) directly measuring the $PM_{2.5}$ capture and identifying the effectiveness of the polyculture mixes in capturing $PM_{2.5}$; b) comparing the effect of configurations A, B, and C, in capturing $PM_{2.5}$; and c) determining the $PM_{2.5}$ capture potential of each species per mix and per configuration, to be compared with the $PM_{2.5}$ capture potential of species in the monoculture.

The decay curve method was used to compare the differential effect of polycultures and monocultures on $PM_{2.5}$ concentration. Four different cases were tested and evaluated:

1. GR polycultures that showed the highest $PM_{2.5}$ capture in the gravimetric test, and greater growth and development of the plants. The best mix was tested in a horizontal position.
2. GW polycultures that showed the highest $PM_{2.5}$ capture in the gravimetric test, and greater growth and development of the plants. The best mix was tested in vertical position.
3. *S. album* as monoculture, which has the highest $PM_{2.5}$ capture as shown by Viecco et al., (2018) (Viecco et al., 2018). The mockups were only tested horizontally representing GR configuration.
4. No-vegetation, which was used as the control case.

3.2.7. Testing of Samples

In total, 8 experimental runs were made for GR and GW polycultures. Each mockup consisted of a mix of three species in a specific configuration i.e. either of A, B, or C. Therefore, 18 mockups were tested in each experimental run covering 5 m^2. Runs 1-4 were carried out for GR polycultures while, runs 5-8 for GW polycultures. In runs 3 and 4, polycultures P1 and P2 were included in the test-module to cover all surfaces with vegetation. Likewise, P11 and P12 were used in runs 7 and 8 for GWs. Table 3-4 shows the polycultures included in each run. Since each mockup was tested twice, plants were washed before and after each test to eliminate $PM_{2.5}$ deposited during nursery stay and testing.

After each run of $PM_{2.5}$ exposure, leaf samples of 50 cm^2 were taken and weighed separately for each species of each mix and configuration. Therefore, a total of sample of 100 cm^2 was collected in two runs for each species of each mockup. These samples were processed using gravimetric analysis to quantify $PM_{2.5}$ capture. Photoshop® 13.0 software was used to study the surface of the leaves

Table 3-4 Polycultures included in each run.

Runs	GI	Polyculture*
1 and 2	GRs	P1, P2, P3, P4, P5, and P6
3 and 4	GRs	P7, P8, P9, P10, P1, and P2
5 and 6	GWs	P11, P12, P13, P14, P15 y P16
7 and 8	GWs	P17, P18, P19, P20, P11 y P12

(*) Each symbol includes the three spatial configurations (A,B,C) in Figure 3-1.

After each run of exposure to $PM_{2.5}$, samples of 50 cm^2 of leaves were taken and weighted separately for each species of each mix and configuration. Therefore, a total of 100 cm^2 sample in two runs was collected for each species of each mockup. These samples were processed using the gravimetric analysis method to quantify $PM_{2.5}$ capture. Photoshop® software was used to determine the surface of the leaves.

3.2.8. Statistical Analysis

The statistical power of 0.9 was considered to the selection of the sample size. To analyze the results of gravimetric test for polycultures, the data were subjected to [4]ANOVA after they were tested for normality using the Shapiro–Wilk test, which is appropriate for small samples. The significance of differences between mean values was tested using Tukey's Test, and a value $p < 0.05$ was considered significant. The tests were carried out using Microsoft Excel (Microsoft Corp., Redmond, DC, USA). To indicate the variability of the $PM_{2.5}$ capture quantified, henceforth all bar charts show mean ± the standard error (SE) with n = 6. The $PM_{2.5}$ capture of all the polycultures studied were reported and compared in Fig. 3-6 and 3-7. Finally, to compare the performance of polycultures and monocultures in the decay curve method, Mann-Whitney Test ($p < 0.05$) was performed using Minitab® 18.

3.3. Results

3.3.1. Comparison of $PM_{2.5}$ Captured by Vegetation in Monocultures and Polycultures

Fig. 3-3 presents a comparison between the $PM_{2.5}$ captured by each species tested as monoculture and polyculture, using the gravimetric method. The results show that in four of the five species studied for GRs, the $PM_{2.5}$ captured by the vegetation was higher in polycultures. The exception is *S. album,* whose $PM_{2.5}$ capture was similar in both scenarios. The relative increase in $PM_{2.5}$ capture of vegetation in polycultures was higher for those species that showed relatively lower $PM_{2.5}$ capture as monocultures.

In polycultures, for the configurations A, B, and C (Fig. 3-1), *S. album* behaved differently than the other species. It showed the highest $PM_{2.5}$ capture in the C configuration, which was 1.57 μ cm^{-2} h^{-1}. In contrast, *L. angustifolia* and *E. karvinskianus* showed the lowest

$PM_{2.5}$ capture in this configuration, i.e. 0.2 μ cm^{-2} h^{-1} and 0.22 μ cm^{-2} h^{-1}, respectively (Fig. 3-4).

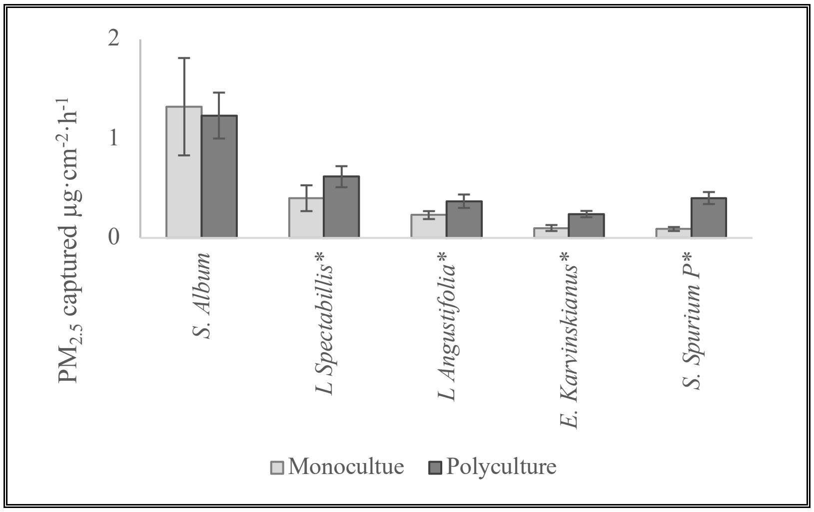

Figure 3-3 Mean $PM_{2.5}$ captured by the GRs vegetation in monocultures and polycultures. Species marked with (*) presented statistically significant differences with 95% of confidence ($p < 0.05$).

In polycultures, for the configurations A, B, and C (see Figure 3-1), *S. Album* presented a different behavior from the other species. For this species, the C configuration — when the species lies on a corner of the mockup — showed the highest $PM_{2.5}$ capture, which was 1.57 μ·cm^{-2}·h^{-1}. In addition, *L. Angustifolia* and *E. Karvinskianus* had the lowest capture for this configuration: 0.2 μ·cm^{-2}·h^{-1} and 0.22 μ·cm^{-2}·h^{-1}, respectively (see Figure 3-4).

It was found that $PM_{2.5}$ capture by the GRs was greater than that by the GWs. Thus, the results show that the positioning of the vegetation i.e. horizontal or vertical, is a key factor affecting $PM_{2.5}$ capture. Fig. 3-5 shows a comparison between *S. album*, *L. spectabillis*, and *S. spurium P* with respect to $PM_{2.5}$ capture, as both GRs and GWs polycultures.

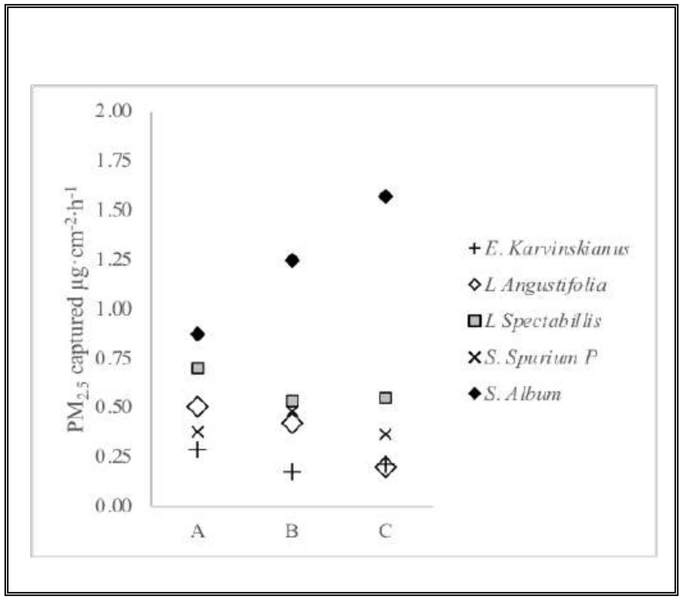

Figure 3-4 Mean $PM_{2.5}$ captured by the GRs vegetation in polycultures according to the configuration: A, B, or C.

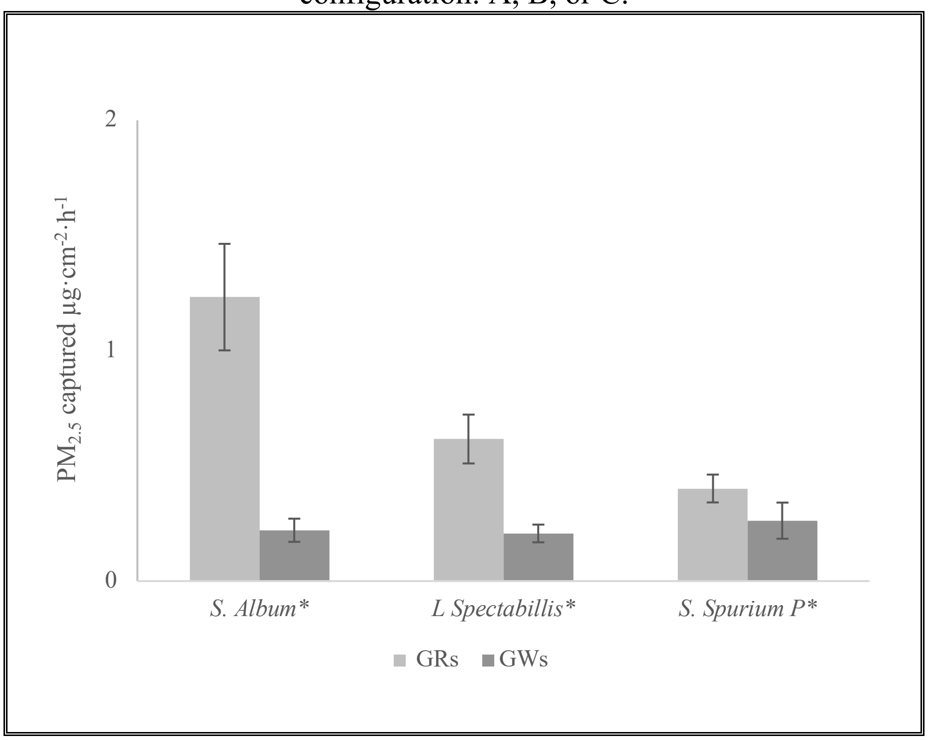

Figure 3-5 Mean $PM_{2.5}$ captured of three species working as GRs and GWs. Species marked with (*) presented statistically significant differences with 95% of confidence ($p < 0.05$).

3.3.2. $PM_{2.5}$ Capture in Polycultures

With respect to GRs and GWs polycultures, statistically significant differences were observed between $PM_{2.5}$ capture of different species. Two groups of GRs polycultures were identified with (a) high and (b) low levels of $PM_{2.5}$ capture (Fig. 3-6). The average $PM_{2.5}$ capture by the polycultures was between 0.3 μg cm^{-2} h^{-1} and 1.2 μg cm^{-2} h^{-1}. Likewise, two groups of GWs polycultures were also identified by their levels of $PM_{2.5}$ capture (Fig. 3-7).

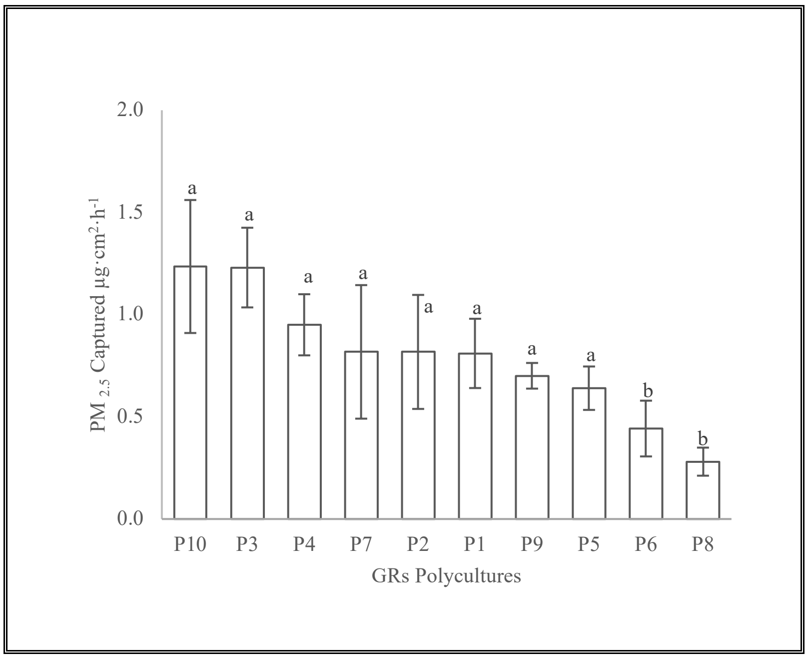

Figure 3-6 Mean $PM_{2.5}$ captured by the polycultures in laboratory conditions in GRs.

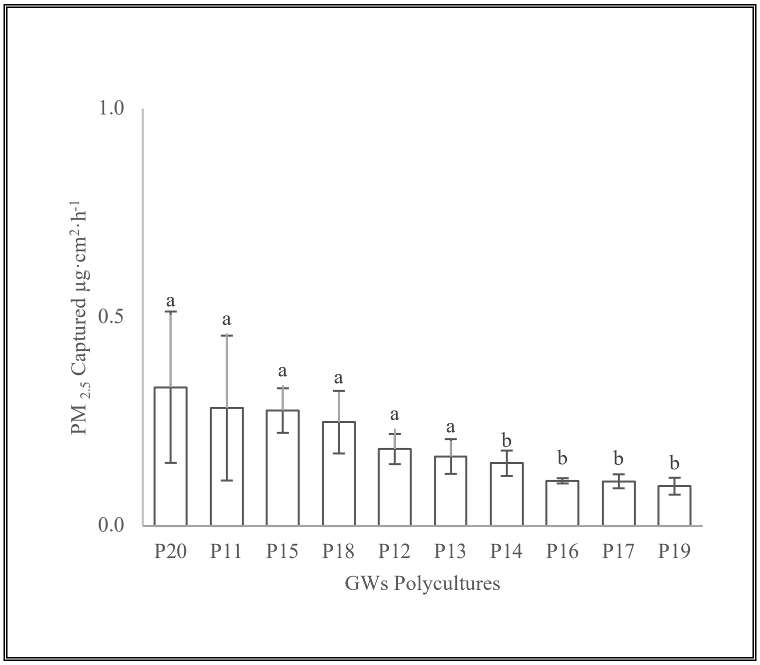

Figure 3-7 Mean $PM_{2.5}$ captured by the polycultures in laboratory conditions in GWs.

3.3.3. Decay Curve Test of Monocultures and Polycultures

Fig. 3-8 shows the decay curve of $PM_{2.5}$ concentrations inside the test-module in four scenarios: without vegetation cover (control), *S. album* as monoculture, and polycultures P4 (GR) and P12 (GW). P4 and P12 were the polycultures which showed the highest $PM_{2.5}$ capture in the gravimetric test and also showed greater growth and development of the plant than other polycultures.

Furthermore, P4 and P12 performed better in reducing the peak $PM_{2.5}$ concentration in comparison with the control and *S. album* monoculture; the decay rate λ was significantly higher in P4 and P12 (Table 3-5). Statistically significant differences ($p < 0.05$) were observed on comparing the $PM_{2.5}$ decay rates of the control and *S. album* monoculture with that of P4 and P12. Lastly, no significant differences were observed between the $PM_{2.5}$ decay rate of P4 and P12.

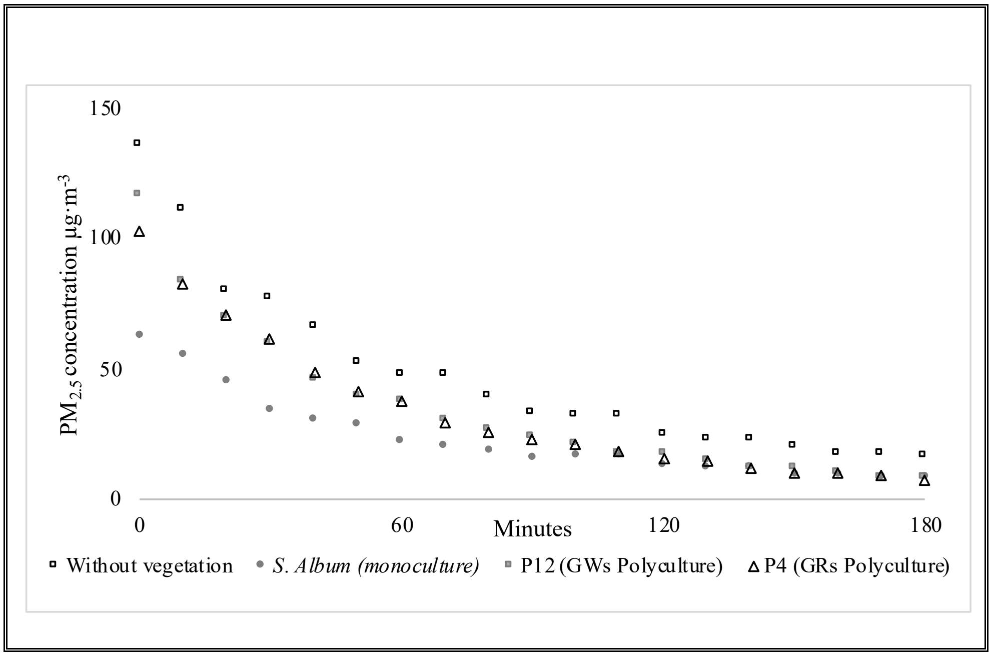

Figure 3-8 Decay curve of $PM_{2.5}$ concentration inside of the test-module with *S. Album* (monoculture), P4 and P12 (polycultures), and without vegetation.

Table 3-5 Parameters of the decay curve of $PM_{2.5}$ concentration

Case	**λ (min^{-1})**	**Standard error**
Without vegetation	0.0105	0.00008
GR polyculture (P4)	0.0137	0.00007
GW polyculture (P12)	0.0135	0.00008
S. album monoculture	0.0101	0.00011

3.4. Discussions

In these experiments, we investigated the impact of biodiversity on the ability to capture $PM_{2.5}$ from GRs and GWs using two methods. Indeed, in most of the cases studied there was a significant increase in the capture of $PM_{2.5}$ of a species located in a polyculture compared to this same in a monoculture.

Four of the five species studied as polycultures increased the ability of the GRs to capture $PM_{2.5}$. These four species were *L. spectabillis, L. angustifolia, E. karvinskianus* and *S. spurium P*. Keeping all other factors constant, since monoculture or polyculture of plants was the only variation in the experimental conditions, the increase in $PM_{2.5}$ capture is attributed to the polyculture GRs. These results complement findings of previous studies which have shown positive interactions between plant biodiversity such as weed and pest suppression, soil nutrient, carbon accumulation (Isbell et al., 2017), and CO_2 and N capture (Jia Yang et al., 2015). Thus, we conclude that biodiversity improves the performance of GRs and GWs in capturing $PM_{2.5}$.

It was also observed that $PM_{2.5}$ capture by *S. album* was negatively affected when it was placed next to *L. angustifolia* in configurations A and B, but not in C (on the mockup's corner). This effect could be because *L. angustifolia* which was approximately 60 cm higher than *S. album* might have blocked the airflow towards the latter. It might have reduced the flow of particles in contact with the surface of *S. album* leaves, thus reducing the number of particles captured by dry deposition. Thus, it is evident that the configuration of the vegetation in polyculture is a key factor that influences the capture of $PM_{2.5}$, and it should be strategically designed to maximize PM capture.

The results also show that when a monoculture has a high potential for capturing $PM_{2.5}$, when configured as a polyculture, its $PM_{2.5}$ capturing potential remains in the same order of magnitude. In addition, when a monoculture has a low potential to capture $PM_{2.5}$, its performance is enhanced by being configured as a polyculture. There was no evidence of a significant decrease in $PM_{2.5}$ capture when a species was put in a polyculture.

A proper biophysical development of vegetation exposed to high concentration of pollutants is crucial to maintain $PM_{2.5}$ capture over time. Therefore, the best polycultures should balance high capture of $PM_{2.5}$ and adequate biophysical development. In this regard, as per the results of our study, we recommend the polyculture mixes P4 and P12 for GRs and GWs, respectively.

Finally, results from decay-curve experiment demonstrate that GRs and GWs polycultures effectively reduce $PM_{2.5}$ concentration, thus improving air quality. The polyculture mixes for GRs and GWs, P4 and P12, respectively, had $PM_{2.5}$ decay rates 30% higher than that of the most efficient monoculture (*S. album*) and the control.

3.5. Conclusions

The potential of $PM_{2.5}$ capture of GRs and GWs made up of seven vegetation species was analyzed under controlled laboratory conditions. The vegetation species were arranged as monocultures and polycultures. Polyculture mixes were tested vertically and horizontally representing GWs and GRs, respectively. Additionally, three different configurations of vegetation were tested for each polyculture mix, each one with varied relative positions of the different plant species within GR and GW mockups. The main conclusions that can be drawn from this work are:

- In most cases, the performance of each species to capture $PM_{2.5}$ was significantly improved when used in a polyculture, as measured by the gravimetric method. However, in an exceptional case, $PM_{2.5}$ capture showed no significant difference in monoculture and polyculture conditions. In conclusion, biodiversity improves the performance of GR and GW vegetation in capturing $PM_{2.5}$.
- Size and spatial position of the vegetation are key factors to be considered to design a configuration that maximizes the capture of pollutants by GRs and GWs polycultures. For example, in the case of *S. album*, the highest $PM_{2.5}$ capture was achieved when the plant was placed in a corner, with other taller plants.
- Polyculture mixes P4 and P12 among GRs and GWs, respectively, showed the best performance, balancing high capture of $PM_{2.5}$ and adequate biophysical

development of the plants. P4 was a mix of *L. spectabillis*, *L. angustifolia*, and *S. album*, while P12 was a mix of three different *Sedums* (*S. palmeri, S. album*, *and S. spurium P*). P4 and P12 polycultures also increased the decay rates of $PM_{2.5}$ particles by 30% in comparison with the best performing monoculture (*S. album*), suggesting that polycultures would be more efficient in capturing $PM_{2.5}$ in the long term.

The results of this investigation can support public policies that promote the implementation of GRs and GWs in cities to improve urban air quality by reducing the levels of ambient $PM_{2.5}$. Moreover, these results could help practitioners to better design these GIs to maximize pollutant capture.

3.6. Acknowledgements

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4. Green Roofs and Green Walls Layouts for Improved Urban Air Quality by Mitigating Particulate Matter

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Abstract:

Urban air quality has been a long-standing problem in most cities worldwide. Many strategies have been proposed to solve it, including green infrastructures such as green roofs (GRs) and green walls (GWs) that provide multiple environmental benefits. Many studies have focused on GRs and GWs strategies to mitigate urban air pollution. However, to the best of authors' knowledge, these studies have not dealt with different urban morphologies, specifically the impact of building heights and coverage ratios of GRs and GWs on mitigating air pollution. Therefore, the potential of GRs and GWs to alleviate air pollution has not been fully exploited. This paper aims to investigate different GRs and GWs layouts and evaluate their efficacy for capturing particulate matter ($PM_{2.5}$) in an urban neighbourhood of Santiago, Chile. We use ENVI-met model to simulate a metropolitan area with buildings, vegetation, paved surfaces, and traffic emissions to estimate air pollution abatement for varying building heights and coverage ratios of GRs and GWs. We simulate these layouts and coverage for a downtown area of Santiago, and results were compared with the base case scenario. Results showed that the air quality improvement by GRs and GWs depends on building height, surrounding urban infrastructure, vegetation cover and proximity to the pollutant source. Specifically, results showed that 50% to 75% of GRs coverage on low-rise buildings could improve air quality

at the pedestrian/commuter level. However, just a 25% coverage of GWs yields the highest $PM_{2.5}$ capture. We conclude that to decrease $PM_{2.5}$ concentrations, priority should be given to instal GRs in buildings lower than 10 m in height. For GWs, the $PM_{2.5}$ abatement is favorable in all cases. ENVI-met results also show that the combined use of GRs and GWs could reduce $PM_{2.5}$ up to 7.3% in Santiago compared to the base case scenario.

4.1. Introduction

Urban air pollution is one of the crucial factors affecting public health for city residents. Exposure to polluted air has been associated with severe health problems that lead to high mortality rates, causing an estimated 7-10 million premature deaths per year worldwide (Mannucci & Franchini, 2017; WHO, 2014). Among different pollutants in the atmosphere, increased exposure to fine particulate matter ($PM_{2.5}$), with an aerodynamic diameter less than 2.5 μm, negatively impacts public health. $PM_{2.5}$ is associated with severe health problems that can lead to death (Anderson, Thundiyil, & Stolbach, 2012; Pope III et al., 2002) and childhood asthma (Dimitrova et al., 2012).

Green infrastructures (GI) reduces pollutants through dry deposition and uptake through leaf stomata and is considered an effective mitigation strategy to improve urban air quality (Cabaraban, Kroll, Hirabayashi, & Nowak, 2013; Tallis, Taylor, Sinnett, & Freer-smith, 2011; Jun Yang, Yu, & Gong, 2008). Recent studies have recognized the vital role of GI in sustainable and resilient urban planning (Sharma et al., 2018). Improvements related to the urban heat island effect, water runoff control, air quality, energy consumption, urban biodiversity are among the benefits of GI (Herrera et al., 2018; Vera et al., 2015, 2017; Victorero et al., 2015; Wuebbles, Sharma, Ando, Zhao, & Rigsbee, 2020).

Specifically, numerous studies on improving urban air quality have focused on trees (Abhijith et al., 2017; Jayasooriya, Ng, Muthukumaran, & Perera, 2017; A. Jeanjean, Buccolieri, Eddy, Monks, & Leigh, 2017; Liu et al., 2018; Wania, Bruse, Blond, & Weber, 2012), grasses (Jayasooriya et al., 2017; A. Jeanjean et al., 2017; Speak, Rothwell, Lindley, & Smith, 2012a), shrubs (Chen, Liu, Zou, Yang, & Zhang, 2015; Dzierżanowski, Popek, Gawrońska, Sæbø, & Gawroński, 2011; Sæbø et al., 2012; Sharma et al., 2016; Viecco et al., 2018), hedges (Abhijith et al., 2017; Santiago et al., 2019; Wania et al., 2012), green roofs (GRs) (Besir & Cuce, 2018; Jayasooriya et al., 2017; Speak, Rothwell, Lindley, & Smith, 2012b; Vera, Viecco, & Jorquera, 2021; Viecco et al., 2018) and green walls (GWs) (Abhijith et al., 2017; Malys, Musy, & Inard, 2014; Ottel, van Bohemen, & Fraaij, 2010; Vera et al., 2021; Viecco et al., 2018). Benefits of trees in urban canyons is debatable. Rather than acting as a sink for air pollutants by particle deposition, trees in congested urban canyons may provide resistance to the canyon flows and reduce vertical mixing and local air circulation. Consequently, local PM concentration increases and urban air quality worsen(A. Jeanjean et al., 2017; Ottel et al., 2010; Wania et al., 2012). Hedges closer to the pollutant source are a better alternative than trees in deep urban canyons due to their reduced capacity to modify canyon air circulation and mixing (Wania et al., 2012). In open urban spaces (e.g., roadside), a combination of a solid barrier and a vegetation cover can help by controlling the outflow and dispersion of vehicular pollutants (Santiago et al., 2019). For open green urban spaces, low ecological landscaping is preferred to lower wind blocking by vegetation. Meanwhile, GRs and GWs provide minimum resistance to the flow over and around the buildings and are aesthetically appealing (Conry et al., 2015; Sharma et al., 2016). All these GI mitigation strategies can increase local ventilation, reduce urban heating and improve urban air quality when properly deployed (Tong, Baldauf, Isakov, Deshmukh, & Max Zhang, 2016).

Numerical models have proven to be useful tools for evaluating the performance of GI mitigation strategies of urban air quality (Jayasooriya et al., 2017), and Table 4-1 summarizes such past numerical modeling studies. Interestingly, we were unable to locate any urban numerical studies on the combined effects of both GRs and GWs on air quality. In this paper we investigate the potential impact of urban GRs and GWs configurations, i.e., spatial layout and coverage, in reducing air pollution by capturing $PM_{2.5}$ in the semiarid climate of Santiago, Chile. Here, the spatial layout refers to the location of GRs and GWs in the urban environment (i.e., GI is located in urban open spaces or street canyons), building height where GI is placed and the distance from the PM source. Coverage refers to the percentage of the available walls and roof building surfaces covered by GWs and GRs. Past studies have shown that the performance of GRs and GWs in capturing the PM varies with different plant species due to their varying morpho-physiological characteristics (Viecco et al., 2018; Jia Yang, Wang, & Xie, 2015). Most of the numerical models shown in Table 4-1 are only based on aerosol dynamics, disregarding the effect of morpho-physiological plant characteristics on dry deposition. This paper also accounts for PM dynamics and vegetation characteristics to provide recommendations for optimal configurations of GWs and GRs for urban planning.

Table 4-1 Past numerical studies used to evaluate urban air quality using different forms of GI.

Model	**Simulation in**	**Pollutant**	**Modelling of**	**City**	**Author**	**Infrastructure**
i-Tree	UFORE	PM_{10}	Removal	Santiago, Chile	(Escobedo et al., 2008)	GRs, shrubs and grasses
	UFORE	NO_2, SO_2, CO, PM_{10} y $PM_{2.5}$	Removal	Melbourne, Australia	(Jayasooriya et al., 2017)	GRs, GWs and trees
	UFORE	NO2, S02, CO, PM_{10}	Removal	Toronto, Canada	(Currie & Bass, 2008)	GRs and shrubs
Open FOAM	CFD (Open source) + sink	$PM_{2.5}$	Concentration change	Leicester City (2 Km)	(A. P. R. Jeanjean, Monks, & Leigh, 2016)	Trees and grass
Open FOAM	CFD (Open source) + sink	PM_{10}	Concentration change	Antwerp, Belgium	(Vranckx, Vos, Maiheu, & Janssen, 2015)	Trees and grass
Open FOAM	CFD (Open source)	$PM_{2.5}$ and NO_X	Concentration and deposition	Marylebone, UK	(A. Jeanjean et al., 2017)	Trees
FLUENT	CFD (Open source)	PM_{10} and NO_X	Concentration (street intersection)	Bari in southern Italy	(Buccolieri et al., 2011)	Trees
FLUENT	CFD (Open source)	PM_{10}	Dispersion particles and concentration (wind tunnel)	Karlsruhe, Germany	(Gromke, Buccolieri, Di Sabatino, & Ruck, 2008)	Trees
RANS	CFD (Open source)	NO_X	Concentration (canyons)	The central region of Seoul, Korea	(Baik, Kwak, Park, & Ryu, 2012)	GRs
ENVI-met	CFD (close)	PM_{10}	Concentration (canyons)	Strasbourg, France	(Wania et al., 2012)	Trees and hedges
RANS	CFD (Open source)	PM_{10} and NO_X	Concentration (canyons)	Mol, Belgium	(Vos, Maiheu, Vankerkom, & Janssen, 2013)	Trees and hedges
WRF and ENVI-met	CFD (close)	PM_{10}	Concentration air	Chicago city	(Conry et al., 2015; Sharma et al., 2016)	Green surfaces
			UHI-Concentrations PM			
			Mesoscale: WRF			
			Microscale: ENVI-met			
WRF	NOAA and NCEP	NO_2	i-Tree + CMAQ + WRF = Vd, Kg rem	Baltimore	(Cabaraban et al., 2013)	Trees
		PM_{10} y O_3	CMAQ: Community Multiscale Air Quality			
			WRF + i-Tree = dispersion, concentration and Rem	Florencia, Italia	(Bottalico et al., 2016)	Trees
PHOENICS	CFD	PM_{10}	Concentration (canyons)	Beijing, China	(Qin, Hong, & Jiang, 2018)	GRs and GWs

4.2. Methods and Numerical Modeling Description

We selected ENVI-met numerical model to study the impact of GRs and GWs on urban air quality. ENVI-met is a three-dimensional, non-hydrostatic computational fluid dynamics model for simulating urban environments (Bruce, 2008). Our assessment of studies in Table 4-1 shows that ENVI-met model advantages over other models. It treats vegetation by factoring in the plant's metabolism to analyze the performance of GRs and GWs in an urban environment. Specifically, ENVI-met considers particle dynamics, vegetation characteristics such as deposition velocity, leaf area index (LAI), and species-dependent metabolisms in simulating urban flows. These considerations are essential in experiment's design, as literature shows that the efficacy of GRs and GWs in capturing PM varies with plant species, due to varying morpho-physiological characteristics (Viecco et al., 2018; Jia Yang et al., 2015). In addition, ENVI-met does not overly parameterize components of urban microclimate. It combines a Reynolds-averaged Navier–Stokes atmospheric model based on the Boussinesq approximation and a k–ε 1.5-order turbulence closure scheme with an explicit treatment of radiative fluxes, vegetation and soil. Multiplies studies have demonstrate that ENVI-met model is capable of predicting meteorological variables (Duarte, Shinzato, Gusson, & Alves, 2015; López-Cabeza, Galán-Marín, Rivera-Gómez, & Roa-Fernández, 2018; Muñoz & Undurraga, 2010; Tsoka, Tsikaloudaki, & Theodosiou, 2018) and species transport and concentrations (Paas & Schneider, 2016) very well.

We selected downtown Santiago of Chile for our study, as it shows high levels of air pollution. Santiago's climate is Mediterranean (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006), and the highest air pollution (Figure 4-1) occurs in the winter season due to low mixing heights, weaker winds and strong thermal inversions enhanced by subsidence (H. Jorquera, Palma, & Tapia, 2000; Héctor Jorquera, 2020; Muñoz & Undurraga, 2010; Villalobos, Barraza, Jorquera, & Schauer, 2015). As a consequence, there is an accumulation of pollution in the lower boundary layer and city canyons such as those in the city center. We implemented the ENVI-met model to simulatea 16-blocks neighborhood in downtown Santiago (Figure 4-6).

4.2.1. Research Methodology

The design of experiments includes the development of three ENVI-met models called the Validation Model (VM), Sensitivity Analysis Model (SAM), and Greener Corridor Model (GCM). The VM was developed to validate the ENVI-met model based on estimating carbon monoxide (CO) as air pollutant. The SAM model includes four blocks of downtown Santiago. It was developed to identify the best GRs and GWs layout and coverage to be used in the GCM. Finally, the GCM includes sixteen blocks in downtown Santiago. It was designed to assess the influence of the urban layout and coverage of GRs and GWs on the air quality at a local urban scale. Table 4-2 shows a summary of the input parameters used for each ENVI-met model and Figure 4-2 and Table 4-2 presents the the resercah methology

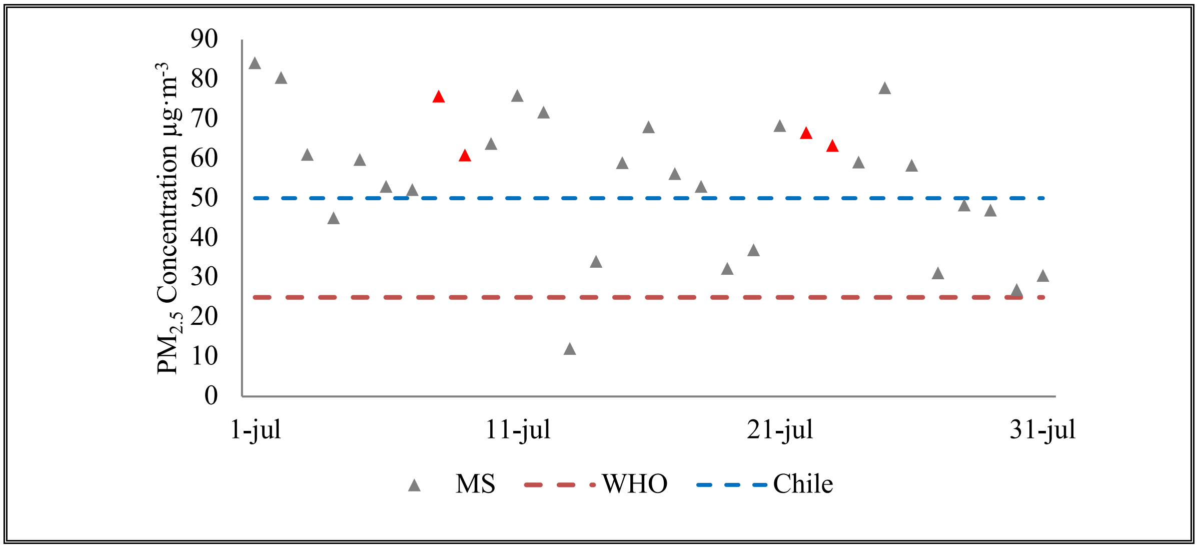

Figure 4-1 Daily ambient $PM_{2.5}$ concentrations in July 2015 (MS Meteorological stations, triangles), WHO and Chilean ambient standards

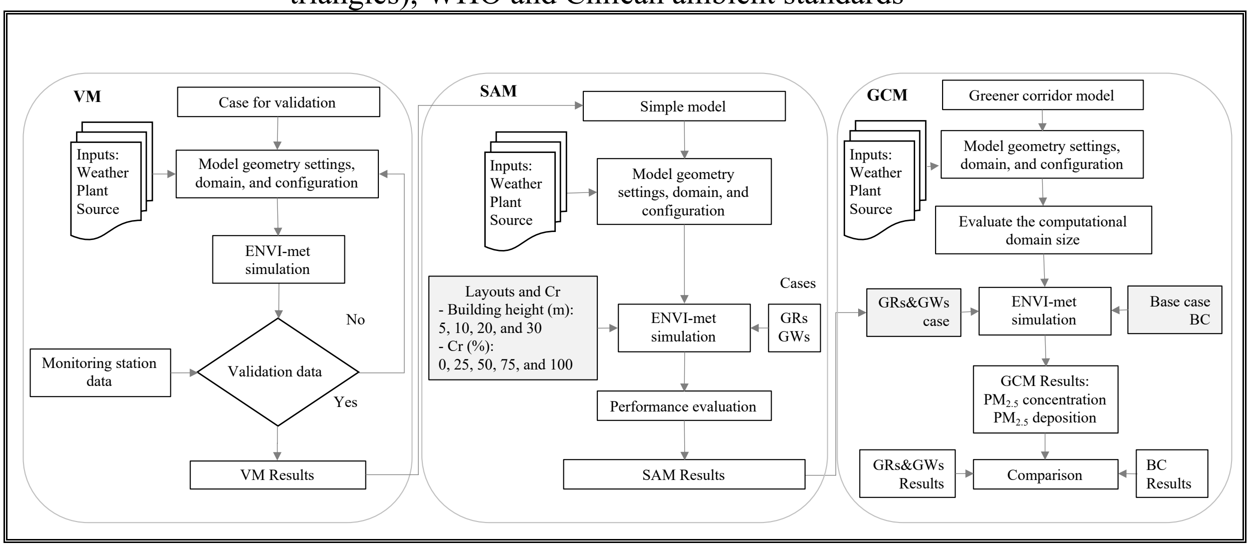

Figure 4-2 Schematic Representation of the methodology

4.2.2. Validation Model (VM)

To validate ENVI-met, we developed an idealized configuration to account for different surfaces and vegetation in our domain of interest of a Santiago´s urban neighborhood (Figure 4-3). Here, we performed four simulations for July 2015. All selected periods were highly polluted and exceeded WHO standards of ambient $PM_{2.5}$ concentration (MMA, 2017). A representative sample was selected for a larger population (Johnson, 2012) with 95% confidence n = 48, which is equivalent to 4 days, considering 12 hours per day. The days were randomly selected for the month with the highest pollution levels in Santiago. Each experiment (highlighted with red triangle markers in Figure 4-1) was performed for 12 hours from 4:00 to 16:00 local time on 8, 9, 22 and 23 July 2015. Observed meteorological variables that influence the dispersion of pollutants, such as temperature, relative humidity (RH), and wind speed are shown in Figure 4-4. The simulated hourly CO concentration was compared with the closest CO monitoring station called Independencia Meteorological Station (MS). We selected CO as an inert tracer pollutant to validate our ENVI-met model and simplified proxy of $PM_{2.5}$ pollution in Santiago. This selection of CO as a surrogate in our design of experiments was based on the following rationale. (a) Unfortunately, Santiago lacks in a reliable pollution inventory for $PM_{2.5}$. Previous studies have illustrated that in the absence of long-range transport, $PM_{2.5}$ is mainly contributed by local traffic sources (vis-à-vis PM_{10} that is comprised of smoke and dust from industrial processes, agriculture, construction, road traffic, plant pollen and other natural sources), and (b) while $PM_{2.5}$ can be produced as secondary aerosols originating from fine sulphates and nitrates, according to previous studies discussed below, on urban scales where ENVI-Met is applied, the contributions of all $PM_{2.5}$ (primary and secondary) is mainly contributed by transportation (combustion sources). Thus, there should be a significant relationship between combustion biproducts

$PM_{2.5}$ and CO. In addition, recent studies over Africa (Rushingabigwi, Nsengiyumva, Sibomana, Twizere, & Kalisa, 2020), Guangzhou city and Pearl River Delta region in China (W. Yang et al., 2020), Phoenix, Arizona and UM/Mexico border (Choi & Fernando, 2008; Choi, Hyde, & Fernando, 2006), and Santiago (Saide et al., 2011; Villalobos et al., 2015) itself, suggest that there is a strong correlation between $PM_{2.5}$ and CO. Thus, CO is a simplified proxy of $PM_{2.5}$ pollution in Santiago due to traffic emissions (Villalobos et al., 2015), and helps circumvent the challenges due to lack of a full pollution inventory for the area that is imperative for accurately simulating chemical reactions. Both $PM_{2.5}$ and CO are emitted simultaneously from traffic, the dispersion of both pollutants is well accounted in the simulations. Note, we do not capture $PM_{2.5}$ transformation due to chemical processes (e.g., secondary particulate matter) because the paper's main goal is to assess the potential of ambient $PM_{2.5}$ capture by GWs and GRs, so it is immaterial how the ambient $PM_{2.5}$ is setup into the modeling domain (by emissions, advection or chemical reactions).

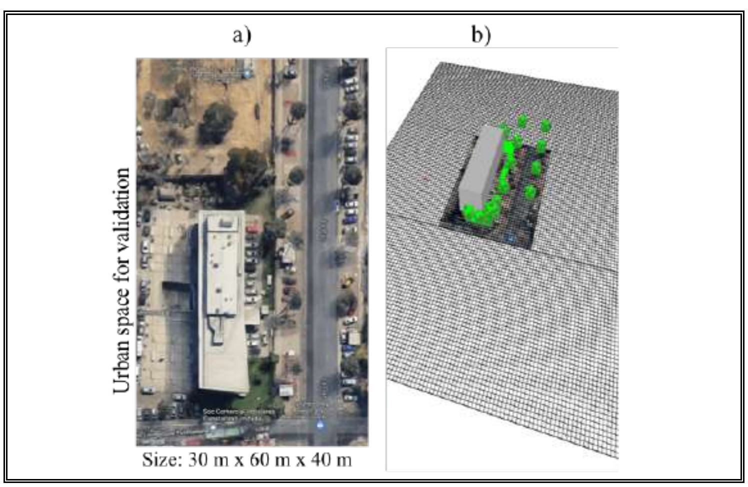

Figure 4-3 Visualization of model domain in validation stage. a. Real image from Google Earth, 2018. b. Visualization in ENVI-met

Table 4-2 Summary of input, test parameters and corresponding values for validation model, sensitivity analysis and greener model.

Description	**VM**	**SAM**	**GCM**
Location	Santiago of Chile (-33.47, -70.66)		
Domain size	90 x 125 x 20, 2L (190 m x 250 m x 40 m)	120 x 120 x 30, 2L (360 m x 360 m x 90 m)	274 x 274 x 50, 2L (822 m x 822 m x 150 m)
Building	16 m x 60 m; h: 12 m	Four blocks	Sixteen blocks
Grid resolution	2 m x 2 m x 2 m (x, y, z)	2 m x 2 m x 2 m (x, y, z)	3 m x 3 m x 3 m (x, y, z)
Start date	July 8, 9, 22 and 23; 4:00 Hrs	July 23; 4:00 Hrs	July 23; 6:00 Hrs
Wind; RHmin; RHmax;	Meteorological station Independencia, Santiago, Chile, Julio 2015		
Source	CO; Line: from (DICTUC, 2016) µg/m·s; rate: 600 s		
Surfaces	Concrete Building; concrete Pavement; Loamy soil		
Green infrastructure	Grass; trees: *Platanus acerifolia, Robinia pseudoacacia, Palma washingtonia and, Sedum album*		
Run	12 hours per day	4 hours	3 hours

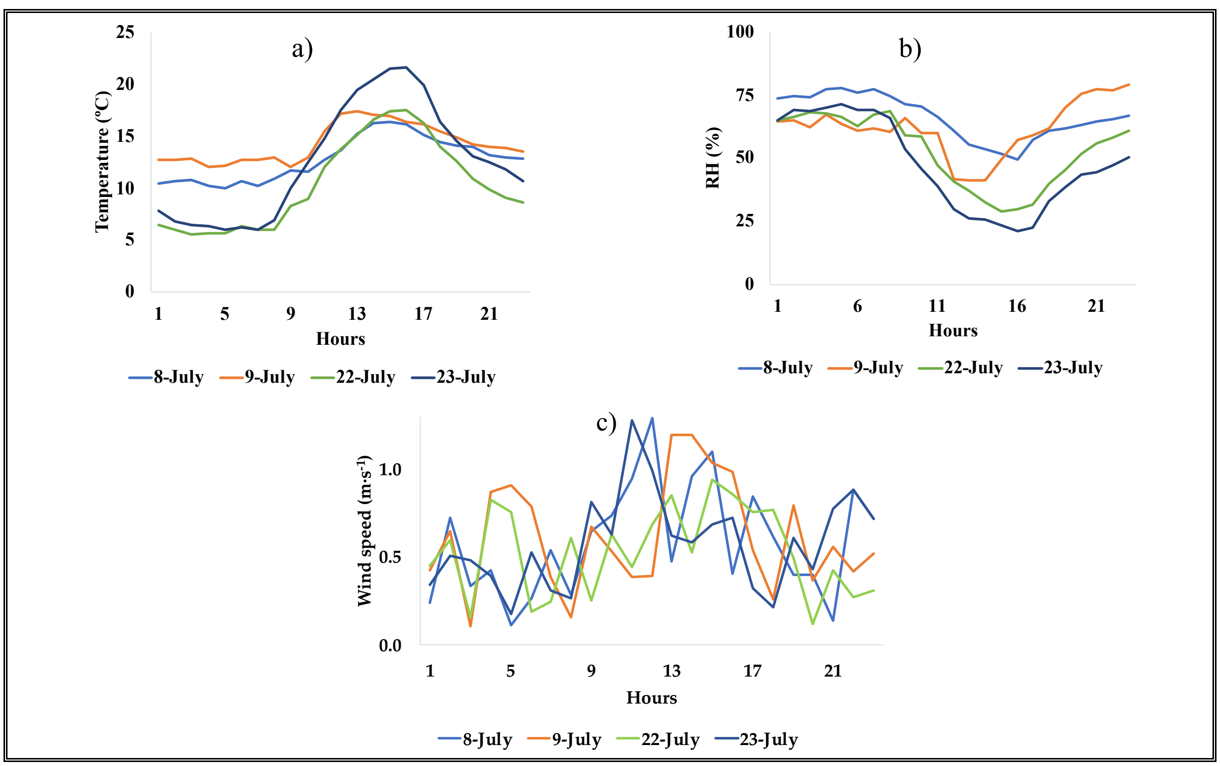

Figure 4-4 Meteorological parameters from Independencia Meteorological Station: (a) temperature, (b) RH, and (c) wind velocity.

4.2.3. Sensitivity Analysis for Ambient $PM_{2.5}$ (SAM)

To identify urban layouts and coverage of GRs and GWs for maximum capture of $PM_{2.5}$ in an urban environment, two cases, one for GRs and another for GWs, were considered, four hours of simulation each. A sensitivity analysis evaluated the effect of GRs and GWs layout and urban coverage on $PM_{2.5}$ capture. The layout refers to the location of GRs and GWs on the buildings. Four building heights were considered (5 m, 10m, 20 m and 30 m). Therefore, GRs are located according to the building height, and GWs cover the whole opaque wall façade along the building height. Additionally, five surface coverage ratios (Cr) of GRs and GWs are analyzed, 0%, 25%, 50%, 75%, and 100%. For GRs, a Cr of 100% corresponds to installing GRs on the total available free area of building roofs, which means that the surface occupied by air conditioning system components and other elements on the roofs are not considered as part of the Cr. The free and occupied roof surfaces were identified with 2018 Google Earth images. Similarly, for GWs, Cr of 100% considers only the available wall surface of buildings to install GWs, excluding windows and doors. Figure 4-5 shows the simulation domain of four blocks of Santiago's downtown; different layouts of GWs and GRs and the studied coverage areas used for SAM are identified. For this experiment, we analyzed ENVI-met modeled $PM_{2.5}$ concentrations at the pedestrian height (1.5 m). Large urban populations are exposed to higher air pollution while walking, biking, or commuting in a city, especially during rush hours when traffic emissions and ambient pollutants concentrations are the highest.

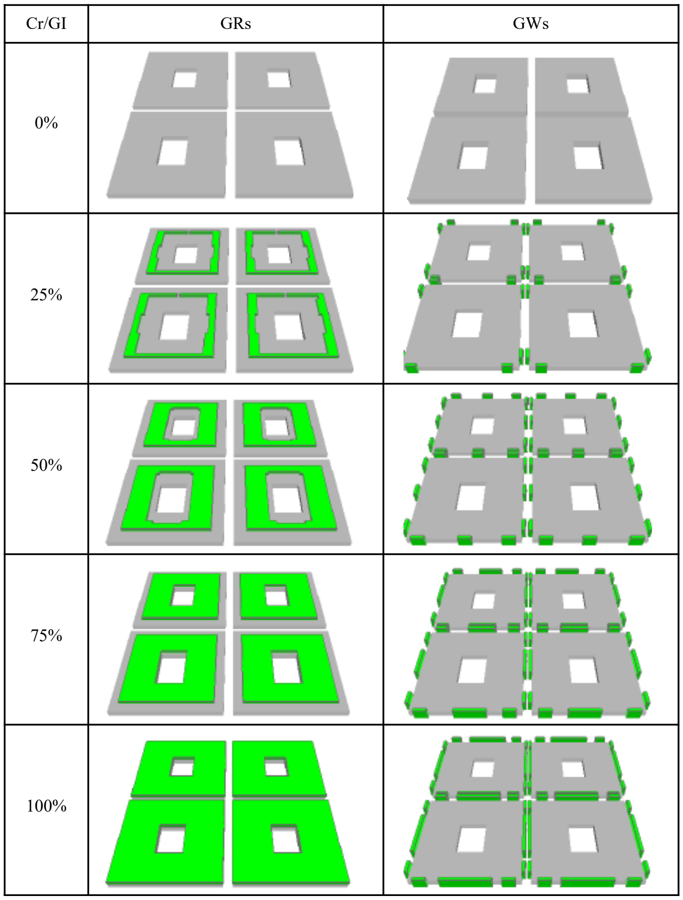

Figure 4-5 Cr in green spaces layout for GRs and GWs sensitivity analysis

4.2.4. Greener Corridor Model (GCM)

Sixteen blocks in downtown Santiago were considered in this case study, as shown in Figure 4-6. It included real buildings, pavement surfaces and GI, including trees. The 3D urban morphology model was created using 2018 satellite images from Google Earth. The different materials included in the model were: concrete for buildings, asphalt for the pavement surfaces, and soil and vegetation in the study domain. The input parameters of GCM are presented in Table 4-2. Simulations were performed for two scenarios: (1) the base case scenario (BC) that represents the current urban morphology, and (2) the green corridor case with hypothetical GRs and GWs on the buildings. We considered SAM results to identify the optimal layout and coverage of GRs and GWs (Section 4.3.2). We computed the total $PM_{2.5}$ deposition in the whole domain and identified four points to analyze the profile of concentrations: P1 is located inside the urban canyon with trees and GRs; P2 is inside of canyon with trees, GRs, and GWs; P3 is in a street interception, and P4 is p'laced in an open space (Figure 4-6).

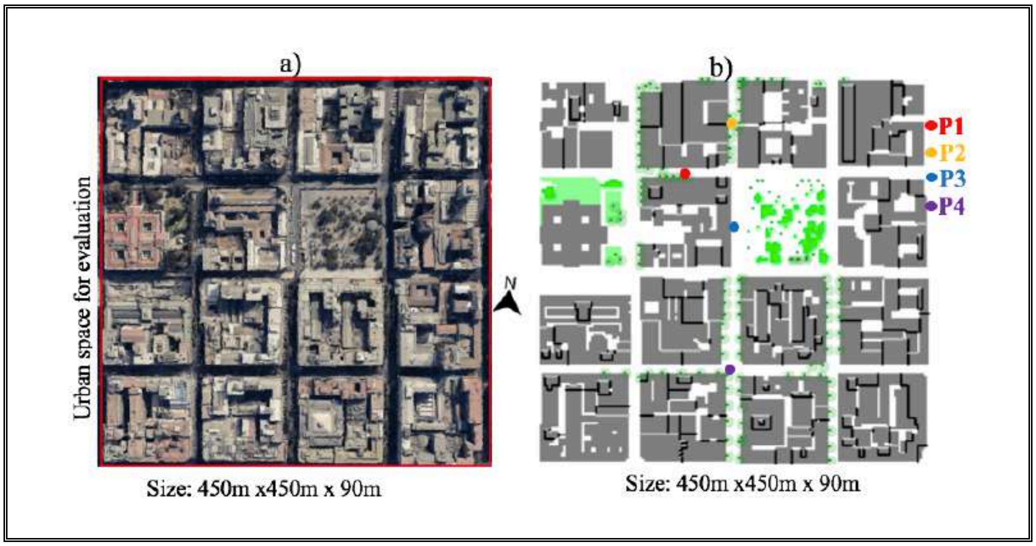

Figure 4-6 Visualization of the green corridor case study, base scenario. a. Satellite images. b. ENVI-met model (plant view) showing locations of analysis P1, P2, P3 and P4

4.2.5. Pollution Source

$PM_{2.5}$ and CO emissions were computed from an equilibrium transport model of the city of Santiago, which simulates an urban transport system considering the capacity of roads and vehicles and the commuters' trip demand spatially distributed across the city (DICTUC, 2016). This equilibrium flow model treats every workday alike. Therefore, the estimated emissions are the same for Monday through Friday for Santiago's transportation network. The background CO concentration for the ENVI-met simulations was equal to the lowest CO concentration between 1 am to 4 am when meager traffic occurs. Figure 4-7 shows the typical traffic CO emission used for VM, SAM, and GCM.

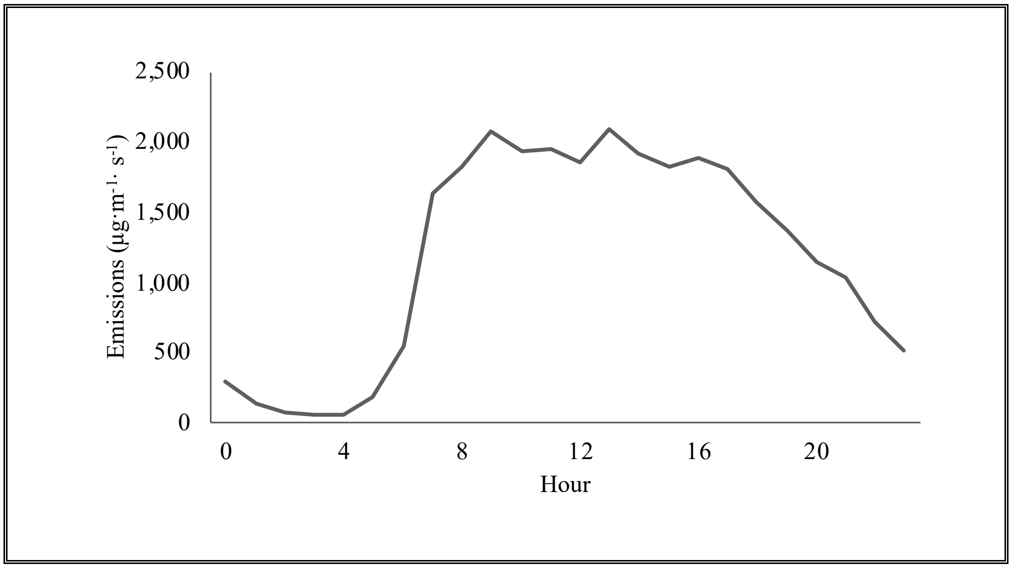

Figure 4-7 CO emissions used in the model (DICTUC, 2016)

4.2.6. Vegetation

The urban vegetation (e.g., trees, grasses, and shrubs) included in VM and GCM closely represent the actual vegetation found at the study site. For GRs and GWs, we used *Sedum album* vegetation type. This species was selected taking into account the results previously reported by Viecco et al., (Viecco et al., 2018) that investigated the capture of PM_{10} and $PM_{2.5}$ of nine species of plants used in GRs and GWs in Santiago. They concluded that *Sedum album* showed the highest potential for capturing PM_{10} and $PM_{2.5}$. Other relevant variables for vegetation used in ENVI-met model were the Leaf Area Index (LAI) of 0.89 $m^3 \cdot m^{-3}$, a $PM_{2.5}$ deposition velocity of 0.23 $cm \cdot s^{-1}$ (Viecco et al., 2018), and 0.15 as albedo (Perez-Blanco, 2010). These variables were measured under laboratory conditions and are adjusted to the vegetation selected here.

4.3. Results and Discussions

4.3.1. Validation of ENVI-met Model

Figures 4-8 and 4-9 show that the simulated CO concentrations for VM agree well with the observations at the Independencia Meteorological Station (MS). Statistical analysis showed a positive linear correlation with an R-square of 0.61 between hourly VM results and Independencia MS. These results reflect that our model setup can account for the turbulent transport of CO in a relatively small domain. Note, this approximation included only CO as a pollutant from traffic exhaust, even though in the real world, multiple types of contaminants from different combustion sources exist. Saide et al. (2011) showed CO-$PM_{2.5}$ correlation coefficient as high as 0.95 using WRF-Chem CO tracer model study over Santiago (Saide et al., 2011). Thus, we can assume that the surrogacy between CO and $PM_{2.5}$ is viable whether chemical reactions are considered or not. The ENVI-met model results in this section show high correlation coefficients and trends between measured and modeled CO. Thus model resutts for $PM_{2.5}$ can be used for making inferences without validation. (Note, the region lacks $PM_{2.5}$ observations and inventory.) Thus, our ENVI-met model experimental design provides a robust setup that estimates reliably pollutants transport phenomena and concentrations of CO and $PM_{2.5}$ for Santiago and a template for regions lacking in $PM_{2.5}$ measurments and inventory.

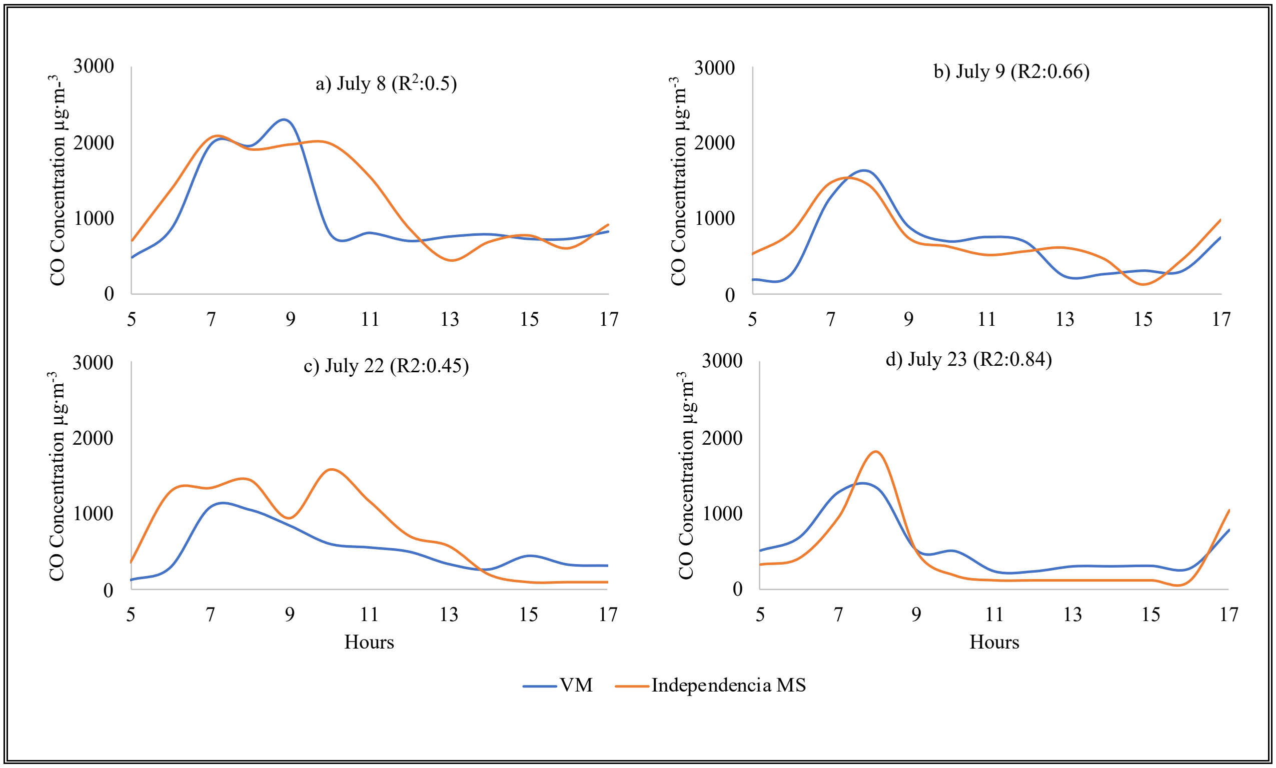

Figure 4-8 VM and Independencia MS daily CO concentrations four days in July

Notice that Figure 4-8 presents a reasonably stringent test for any dynamical air pollution model — see (Belis et al., 2019), for examples — because simulated and observed data are paired in time and space. The scattering of points around the regression line may be ascribed to a) weekly variability in actual emissions, b) advection of CO from nearby — not modeled — roads, c) vertical mixing with urban background air. The best agreement between simulated and monitored CO concentrations of the VM was on July 9 and 23 (Figures 4-8 (b) and 4-8 (d)). On the other hand, results for July 8 and 22 (Figures 4-8 (a) and 4-8(c)) showed lower agreement. This could be explained because the model considers only transport emissions related to work-home trips, and it does not include small-scale factors like commercial activity around the zone. For example, close to the study area, each Wednesday, a free marketplace is installed, which could increase the levels of pollutants recorded at the monitoring station due to extra freight and shopping activities

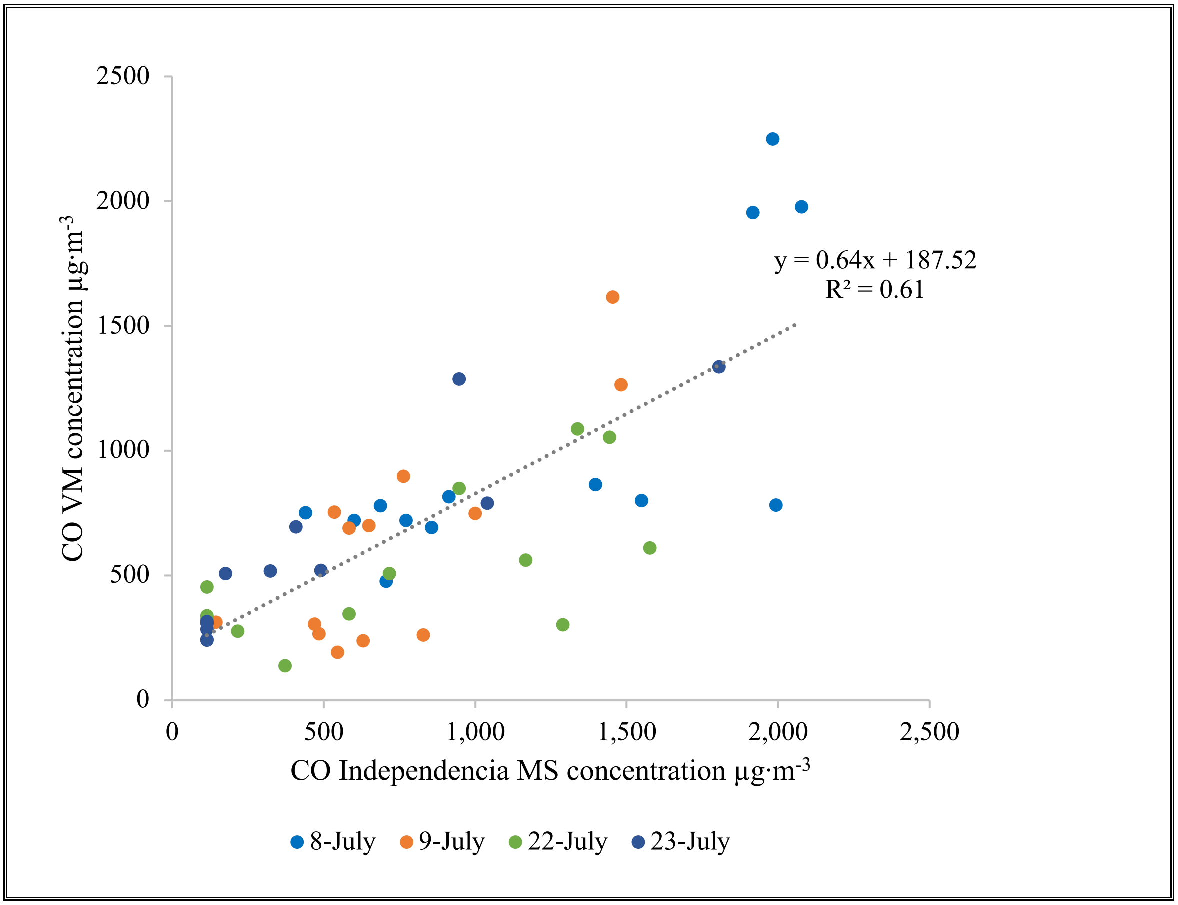

Figure 4-9 Correlation between CV and Independencia MS CO concentration

4.3.2. Sensitivity Analysis from SAM

Figures 4-10 and 4-11 show the percentage variation of $PM_{2.5}$ concentration for differentcoverage ratios (Cr) for GRs and GWs, respectively. GRs cause the highest reduction in $PM_{2.5}$ concentrations for building heights of 5 and 10 m (Figure 4-10). While $PM_{2.5}$ concentration is reduced 3.7% for 100% Cr of GRs in buildings with 5 m height (Figure 4-10a), a reduction of 2.7% of $PM_{2.5}$ concentration is observed in building with 10 m height and 100% Cr (Figure 4-10b). On the other hand, GRs at buildings heights of 20 and 30 m did not improve air quality at the pedestrian level. Also, Cr of 75% and 50% GRs at building height of 5 m and 10 m, respectively, causes as much $PM_{2.5}$ concentration decrease as Cr of 100% at the same height. Therefore, the reductions in $PM_{2.5}$ concentration with GRs are dependent on the height that the GRs are located and Cr.

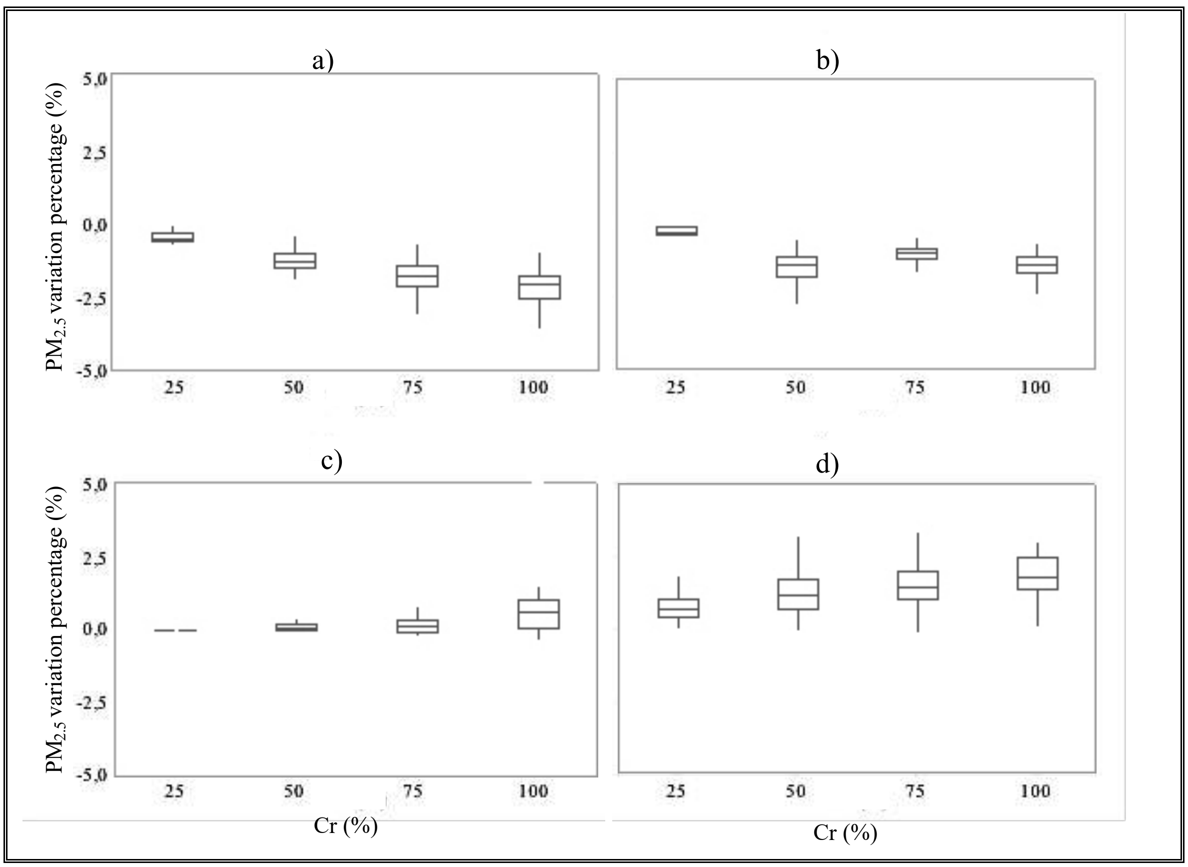

Figure 4-10 $PM_{2.5}$ percentage variation with different coefficient ratio Cr in GRs at the pedestrian level. Height: a) 5m, b) 10 m, c) 20 m and d) 30 m

While GWs show a reduction in $PM_{2.5}$ concentration up to 15% for all cases (Figure 4-11), higher Cr values show marginal improvements in $PM_{2.5}$ concentration. Simulation results showed that Cr of 25% is optimum to improve air quality at the pedestrian level by GWs.

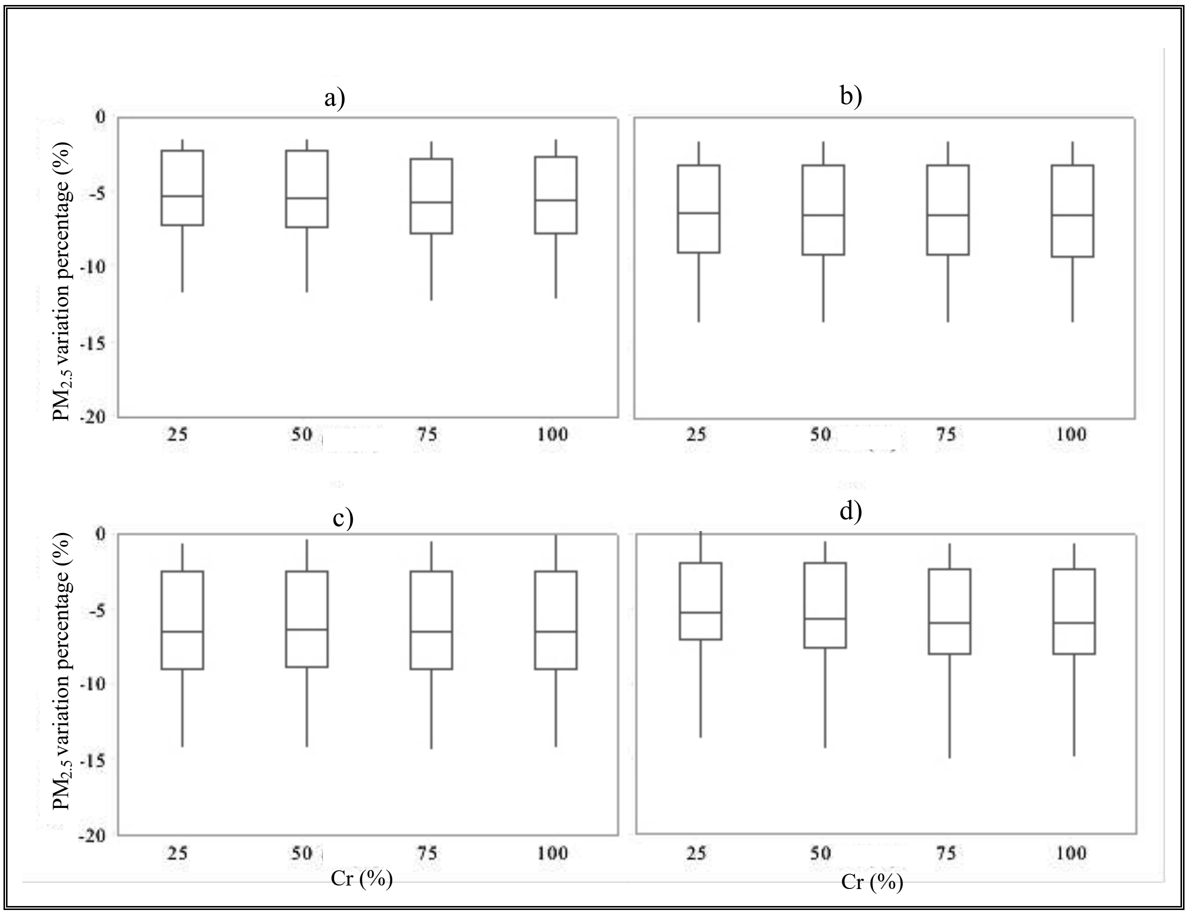

Figure 4-11 $PM_{2.5}$ percentage variation with different coefficient ratio Cr in GWs at the pedestrian level. Height: a) 5m, b) 10 m, c) 20 m and d) 30 m

Figure 4-12 (a) shows $PM_{2.5}$ concentrations for cases with 100% and 0% Cr inside a street, according to cross sections A-A' (GRs) and B-B' (GWs). The highest pollutant levels are inside the street canyons, and the concentration decreases away from the source. Thus, GRs works best in low-rise buildings. Comparing the results of Figures 4-12a and 4-12b, we found that GWs are more effective than GRs to reduce $PM_{2.5}$ concentration due to the proximity of vegetation to the emission source and larger GWs surface area.

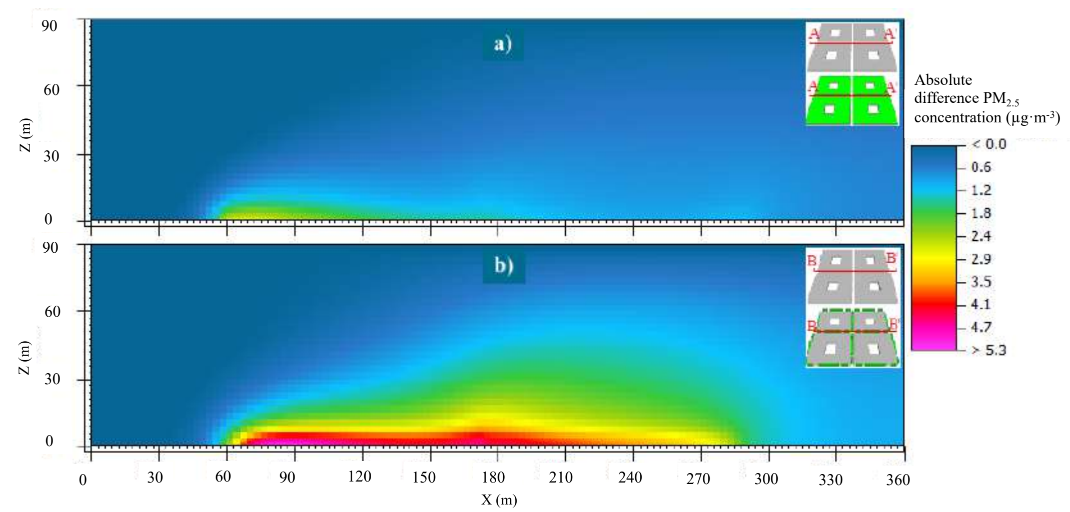

Figure 4-12 Variation $PM_{2.5}$ concentration profile inside a street for buildings with 5 m height. a) GRs SAM Cr 100% versus Cr 0% A-A'. b) GWs SAM Cr 100% versus Cr 0%

4.3.3. Influence of GRs and GWs on Urban Air Pollution Mitigation

This section presents the influence of GRs and GWs on the air quality of green corridor case study (GCM). Two types of results are shown, $PM_{2.5}$ concentrations and $PM_{2.5}$ depositions on GWs and GRs for the GCM and base case (BC - without GRs and GWs).

Figure 4-13 shows $PM_{2.5}$ concentration at 1.5 m height (pedestrian/commuter level) between the base case (BC) and GCM. Overall, the $PM_{2.5}$ concentrations at the pedestrian/commuter level did not decrease with GWs and GRs for 3 hours. We identified four points to analyze the concentration profiles (see: methodology above).

With the presence of trees, GRs, and GWs, ENVI-met model showed an increase in $PM_{2.5}$ concentration profiles in P1 (Figure 4-14a) at the pedestrian level, likely due to an increase in roughness and a decrease in canyon wind speeds. Here the aerodynamic (drag) effects prevailing over the deposition effects. Dense trees in street canyons likely have a negative impact on $PM_{2.5}$ due to reductions in air circulation and decreasing low-level turbulence. These findings agree with other studies that investigated the effect of trees in street canyons (A. Jeanjean et al., 2017; Tong et al., 2016). Therefore, we suggest GRs only in canyons, and installation of GWs should be done with caution. Besides, ENVI-met simulations showed that trees in urban canyons do not improve urban air quality, although they are known for environmental and social benefits (e.g., Heat Island reduction). Figure 4-14b shows that the rate of decrease per unit meter of height was 42% more for GRs and GWs than that for the BC. Similar effect was found at the street intersection P3 and the open space P4. The $PM_{2.5}$ concentrations with GRs and GWs were 35% and 57% higher than the concentration of the BC (Figures 4-14c and 4-14d).

On the other hand, comparing $PM_{2.5}$ depositions at all the surfaces of the model, the case with GRs and GWs demonstrates better performance than the BC, in that GRs and GWs increase the capture of $PM_{2.5}$ by 7.3% compared to BC. The deposition results show that the highest deposition levels are between 7.5 m to 16.6 m (Figure 4-15). This result agrees with Ottel et al., (2010) who concluded that the proximity to the source increases $PM_{2.5}$ deposition on vegetation. This result means GRs and GWs could remove up to 7.3% of $PM_{2.5}$ from polluted air compared with the urban morphology of the BC. Finally, we note that a positive impact of $PM_{2.5}$ depositions in GCM was found due to a larger deposition surface and increased residence times within the street canyons that enhances deposition. Nevertheless, changes in $PM_{2.5}$ concentration was non-uniform throughout the simulated urban domain and were dependent on meteorology.

4.4. 4. Conclusions and Recommendations

We implemented an ENVI-met model over a Santiago's urban neighborhood and evaluated multiple scenarios of green roofs and green walls. This study was constrained by the lack of a pollution inventory. We used available nearest CO station measurements as a surrogate for $PM_{2.5}$ emitted (or precursors are emitted) due to transportation. We caution the readers to exercise circumspection when interpreting results of the manuscript due to this limitaiton. Note, as highligted in Section 4-2 on Methods and Section 4-3 on Results, such proxy studies are valuable for heat, air quality, and flood mitigation assessment studies that could inform decisions to make developing cities and communities lacking in extensive observations more sustainable and resilient.

The main conclusions of this paper are the followings:

- GWs have a more significant impact than GRs got improving air quality. Based on SAM results, the proximity of GRs and GWs to the emission source and green coverage ratio (Cr) are key factors underlying improved air quality at the pedestrian/commuter level, which should be considered in urban design and planning. The results showed that $PM_{2.5}$ concentrations are reduced by 3.7% and 2.7% for buildings with GRs and heights of 5 m and 10 m, respectively. On the other hand, $PM_{2.5}$ concentration decreases up to 15% for GWs.

- Coverage ratio (Cr) of GRs and GWs is a key factor determining the performance of $PM_{2.5}$ capture of GRs and GWs in an urban area. We found that the optimum $PM_{2.5}$ capture does not occur at Cr = 100%. This means that optimum Cr values must be evaluated based on simulations for specific traffic and urban morphology.
- GRs and GWs remove up to 7.3% of $PM_{2.5}$ from polluted air based on the GCM. The implementation of GRs and GWs at the same time has a positive impact on $PM_{2.5}$ deposition.

Based on the above research, the following recommendations are proposed for the use of GWs and GRs in urban planning and design of downtown Santiago, Chile to mitigate air pollution by fine particle matter:

- Priority should be given to installation of GRs in buildings lower than 10 m height. For GWs, the effect is more extensive in all cases because they are installed on the building façade exposed to traffic.
- The Coverage ratio (Cr) should be 75% and 50% for GRs on buildings of 5 and 10 m height, respectively. While for GWs, a Cr of 25% is suggested for all cases.

- Dense trees in street canyons combined with GWs should be avoided because trees cause a reduction of air circulation and a consequent increase of $PM_{2.5}$ concentrations that lead to deterioration of air quality at the pedestrian level.

The above quantitative findings and recommendations are specific to GRs and GWs implementations in Santiago, Chile. However, the presented results could guide urban planning for cities with similar climate and urban morphology, and the research methodology is portable to other cities lacking in exhaustive emission inventory. Finally, GRs and GWs are excellent choices to mitigate air pollution in urban environments, especially when GRs and GWs are placed strategically to obtain the best coverage area, proximity to the source of exposure, location with respect to surrounding buildings and other existing GI.

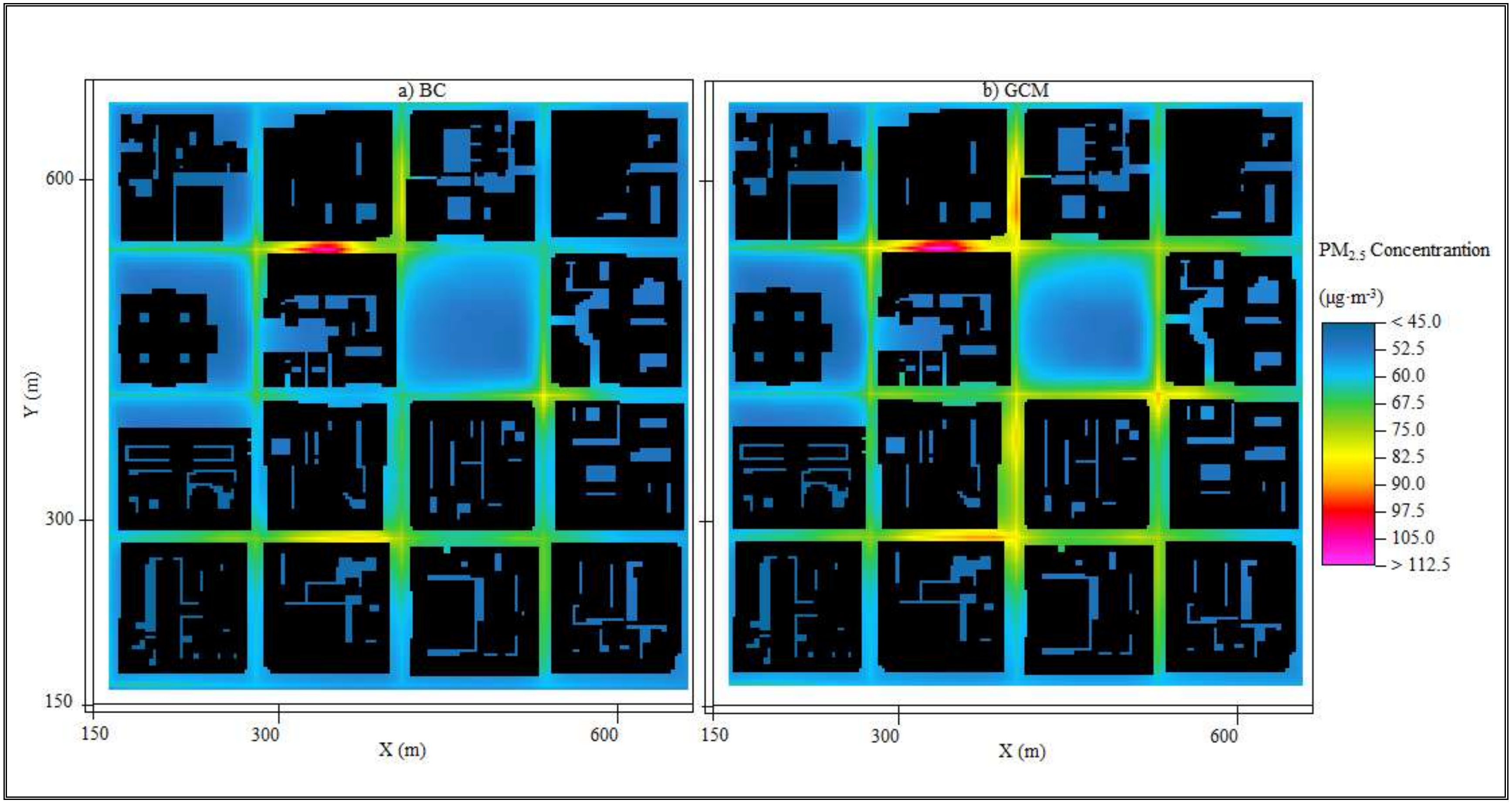

Figure 4-13 $PM_{2.5}$ concentrations in the urban environment for two cases:a) BC and b) GCM.

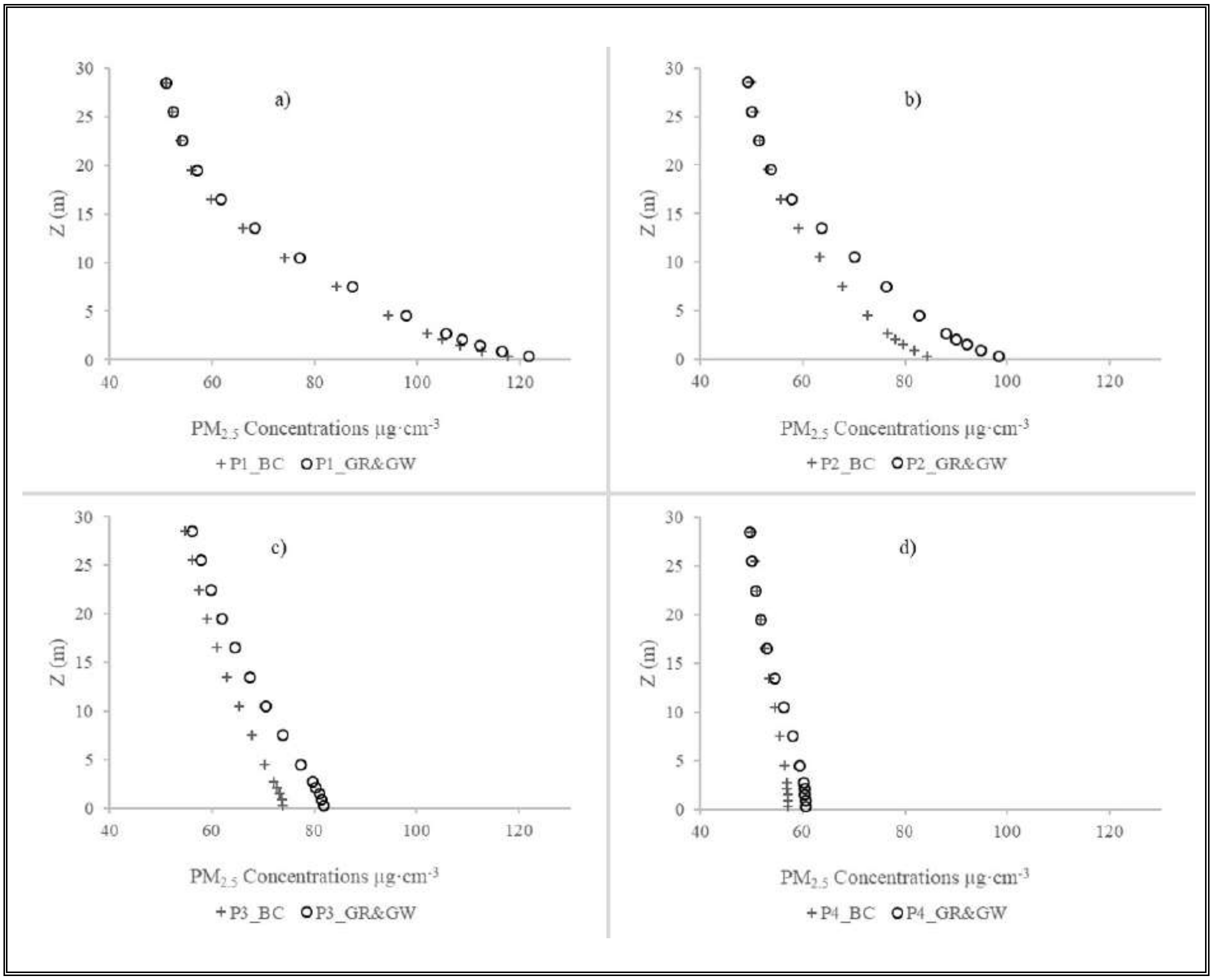

Figure 4-14 Profile of $PM_{2.5}$ concentrations for base case (BC) and GCM (GRs & GWs) in four points: a) P1 inside of canyon with trees and green roofs GRs; b) P2 inside of canyon with trees, green roofs GRs and green walls GWs; c) P3 an interception and d) P4 in an open space

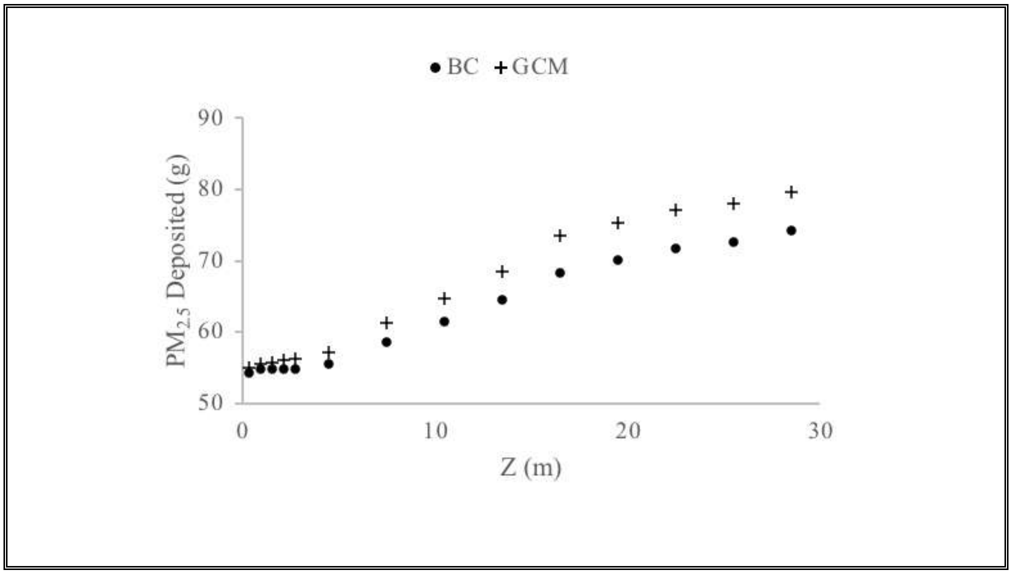

Figure 4-15 Profile of $PM_{2.5}$ deposited on all surfaces for BC and GRs and GWs.

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5. GENERAL CONCLUSIONS AND FUTURE WORK

5.1 General Conclusions

GRs and GWs generate multiple benefits to people and the urban environment. Among the most notable benefits are building energy efficiency, rainwater runoff management, biodiversity and improvement in urban air quality. In this research, a study was conducted to assess the impact of GRs and GWs on PM abatement in a city, focusing on the vegetation type and configurations on the buildings where they are installed.

The hypotheses proposed for the development of this research were analyzed and following results were obtained:

H1. *Of the species most used in GRs and GWs in Santiago, the Sedum family are effective in contributing to urban atmospheric decontamination by* PM_{10} *and* $PM_{2.5}$: Has been quantified the dry deposition of PM ($PM_{2.5}$, PM_{10} and wax) of several vegetation species commonly used in GWs and GRs in semiarid climates. An experimental method was implemented to evaluate the dry deposition of PM for nine species (P. *Tobira, L. Angustifolia, L. Spectabillis, S. Album* and *S. Reflexum* for GRs and *A. Cordiflora, E. Karvinskianus, S. Palmeri* and S. *Spurium P*. for GWs). These species are the most used in semiarid climates of Central Chile. The results demonstrated that there are differences between vegetatives species in capturing PM. *S. Album* is the GRs and GWs most effective specie to capture PM_{10} and $PM_{2.5}$. Specific conclusions are presented in chapter 2.

H2. *The plant species biodiversity significantly improves the performance of GRs and GWs to capture PM, and proper combinations of plants can favors the capture of PM.* Has been demonstrated that just as plant biodiversity can improve other aspects in agroecosystems, it can also improve the performance of GRs and GWs vegetation in capturing $PM_{2.5}$. The method implemented demonstrated that the combination of *L Spectabillis*, *L Angustifolia* and *S. Album* is a polyculture that showed the best performance balancing high capture of $PM_{2.5}$ and biophysical development for GRs. While, *S. Palmeri, S. Album and S. Spurium P* showed the best performance in capturing GWs. In chapter 3, other conclusions are presented.

H3. *H3. A reduction of air pollution by PM2.5 of 15% is achieved with the installation of GRs and GWs on the most appropriate surfaces of an urban area*. Has been validated by implementing an ENVI-met model over an urban neighborhood of Santiago. The results showed that $PM_{2.5}$ concentrations are reduced by 3.7% and 2.7% for buildings with GRs and heights of 5 m and 10 m, respectively. On the other hand, $PM_{2.5}$ concentration decreases up to 15% for GWs. The use of GRs and GWs removes up to 7.3% of $PM_{2.5}$ from polluted air. The implementation of GRs in combination with GWs has a positive impact on the $PM_{2.5}$ deposition. Rebuted conclusions and specific recommendations are presented in chapter 4.

The results presented in this dissertation contribute to assess the performance of GRs and GWs for urban air quality. Specifically, recommendations for vegetation types and polyculture configurations, coverings and location were generated. Moreover, this result can support policies that promote implementation of GRs and GWs to improve urban air quality by $PM_{2.5}$ in cities.

5.2 Limitatations Future Work and Recomendations

This study focused on the analysis and quantification of PM capture from GRs and GWs to improve urban air quality. The first and second objectives required the development of a laboratory work inside a test-module that allowed to measure the performance of GRs & GWs vegetation in capturing PM. In this process there were problems, some were successfully solved for others. The following solutions are recommended as part of future work.

- Infiltrations: It took a long time to seal the thermal bridges until it reached infiltrations of 0.34 ACH. Thus, it is suggested to define a methodology to identify the parts of the test module structure where the greatest infiltrations occur and perform the subsequent sealing.
- Pollutant: For the generation of PM, several alternatives were explored, being the clean burning of incense the strategy that allowed the test to be replicated as many times as necessary. However, a more successful way could be defined for this process using some type of alternative mechanism, such as the use of particle generators which were not considered in this investigation because of their high cost.
- Vegetation: In this study, 9 species of vegetation used in GRs and GWs in Santiago were considered. Taking in to account the adaptability of native

vegetation, these could be evaluated in future research. With this information, it will be possible to create a vegetation database of GRs and GWs with defined capture capacity to be recommended in urban planning and design in each geographic location.

- Weather conditions: Inside the test module, the weather conditions of a winter day in Santiago were replicated, because air pollution is worse in Santiago in this season. For future research, a study in different climates is required, considering that the performance of the vegetation could be different under different weather conditions.

The impact of the vegetation use for GRs and GWs were modeled in an urban area with the use of ENVI-met. Some recommendations are submitted for further exploration as an environmental solution:

- Architectural and material properties: for future modeling experiences with ENVI-met, it is suggested to simplify some architectural and material properties as this may require a lot of computational resources.
- Climatic conditions: different wind velocities may be examined for different scenarios and climates in future investigations. Additionally, wind measurements can be added to evaluate the ENVI-met model, using high-precision anemometers.
- Validation: for the validation of the model, the generation of CO from transport emissions was considered. However, to have a closer approximation, sources of PM could be considered.

- Trees: To generate design recommendations for GRs and GWs in order to improve air quality in urban planning, it is suggested to explore other configurations of trees in combination with GRs and GWs as future work.
- In this study, the potential of vegetation simulating critical air quality conditions was analyzed in an environmental chamber; therefore, the results of this study could be compared with tests subjected to real environmental conditions as future research.
- The results of PM capture of polycultures demonstrated an improvement in the performance of the vegetation taking into account the configurations used. Based on this, for the creation of polycultures it is recommended to consider characteristics that strongly impact the survival of the vegetation used, such as irrigation needs, maintenance and tolerance to extreme temperatures. The use of native vegetation could be evaluated.
- In this research, the influence of the coefficient ratio and height of the building on the capture of PM at the pedestrian level was explored. For a better understanding of the impact of design conditions and the environment on the performance of GRs and GWs, other factors such as size of the plant, position of vegetation, nearby infrastructures, among others, could be evaluated in future research., more investigation is needed.
- It is suggested as a part of future work for evaluate a proposal for GRs and GWs that balances the benefits of these green infrastructure in an ideal design.

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