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Effects of biodiversity in green roofs and walls on the capture of fine particulate matter

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A R T I C L E I N F O

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A B S T R A C T

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 pollutants. Choosing appropriate designs of 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: *Sedum 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 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 that polycultures could be more effective in long-term reduction of high $PM_{2.5}$ concentrations.

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 green infrastructures (GI) such as trees (Cabaraban et al., 2013; Jayasooriya et al., 2017; Jeanjean et al., 2017), shrubs, hedges (Wania et al., 2012; Abhijith et al., 2017), green roofs (GRs) (Wania et al., 2012; Abhijith et al., 2017; Yang et al., 2008), and living walls (GWs) (Abhijith et al., 2017; Ottel et al., 2010; 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 and 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, 2016). 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 (WHO, 2016; Burnett et al., 2018; Hamanaka and Mutlu, 2018; Pope and Dockery, 2006; Chow et al., 2006).

The use of GRs and GWs in cities is feasible due to the presence of buildings with large areas available to accommodate them (Mohajeri et al., 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 et al., 2008).

Literature review shows a positive impact of monoculture vegetation

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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 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 and Bauerle, 2012; Kiær et al., 2009; Zhang et al., 2017; Upadhyaya and Blackshaw, 2007). 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.

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 et al., 2010). Increased plant productivity could improve rooftop insulation, reflectance, and cooling from evapotranspiration (Alexandri and Jones, 2008; Kumar and Kaushik, 2005; Verheyen et al., 2008). Higher complexity of vegetation could also increase rainwater retention (Dunnett et al., 2008; Rixen and Mulder, 2005). Moreover, biodiversity of plants could reduce the need for fertilizer (Bracken and Stachowicz, 2006; Cardinale, 2011; Berndtsson, 2010), 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 et al., 2007; Nagase and 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 (Yang et al., 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.

2. Materials and methods

2.1. Methods of measuring $PM_{2.5}$ capture

Two methods have been identified to determine the effect of vegetation on improving air quality through particle capture: gravimetric analysis and decay curve.

Table 1
$PM_{2.5}$ capture of monocultures (derived from data of Viecco et al. (2018)).

Species	$PM_{2.5}$ (μg cm^{-2} h^{-1}) Mean	SD	Plant type
Sedum 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

2.1.1. 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), and adapted and implemented by 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 were measured. Further details of this method can be mentioned in detail in 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.

2.1.2. Decay curve method

In this method, the vegetation was exposed to a high concentration of $PM_{2.5}$ into a test-module for 3 h and 40 min, 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 min, (2) attaining the peak of $PM_{2.5}$ concentration, and (3) decay of $PM_{2.5}$ concentration for 3 h. 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 et al., 2007). $PM_{2.5}$ concentration inside the test modules is given by:

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

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.

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) 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 (33°44′ S, 70°67′ W). This city is characterized by a semiarid climate (Kottek et al., 2006).

The criteria used to select these species were: (1) $PM_{2.5}$ capture per deposition surface as shown in Table 1; (2) irrigation 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 2).

Table 2
Criteria for vegetation selection.

Factor	Level		Criteria	Weight assigned
$PM_{2.5}$ Capture	L1	Low	3 species with the lowest capture	50 %
	L2	Medium	3 species with intermediate capture	
	L3	High	3 species with the 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, growth of weeds, susceptibility to pests, and renewal period	25 %
	L2	Medium		
	L3	High		

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 1).

2.4. Design of polyculture mixes

Based on the criteria presented in Table 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 GR 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 GR polycultures, while another ten three-species mixes were analyzed as GW 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 (Vera et al., 2017; Sandoval 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. 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.

2.5. Description of the experiment

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

2.5.1. Testing conditions

The experiments were carried out in a test-module under controlled indoor conditions as shown in Table 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 et al., 2017).

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

2.6. Analysis of $PM_{2.5}$ 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). The mockups were only tested horizontally representing GR configuration.
4 No-vegetation, which was used as the control case.

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 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.

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 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,

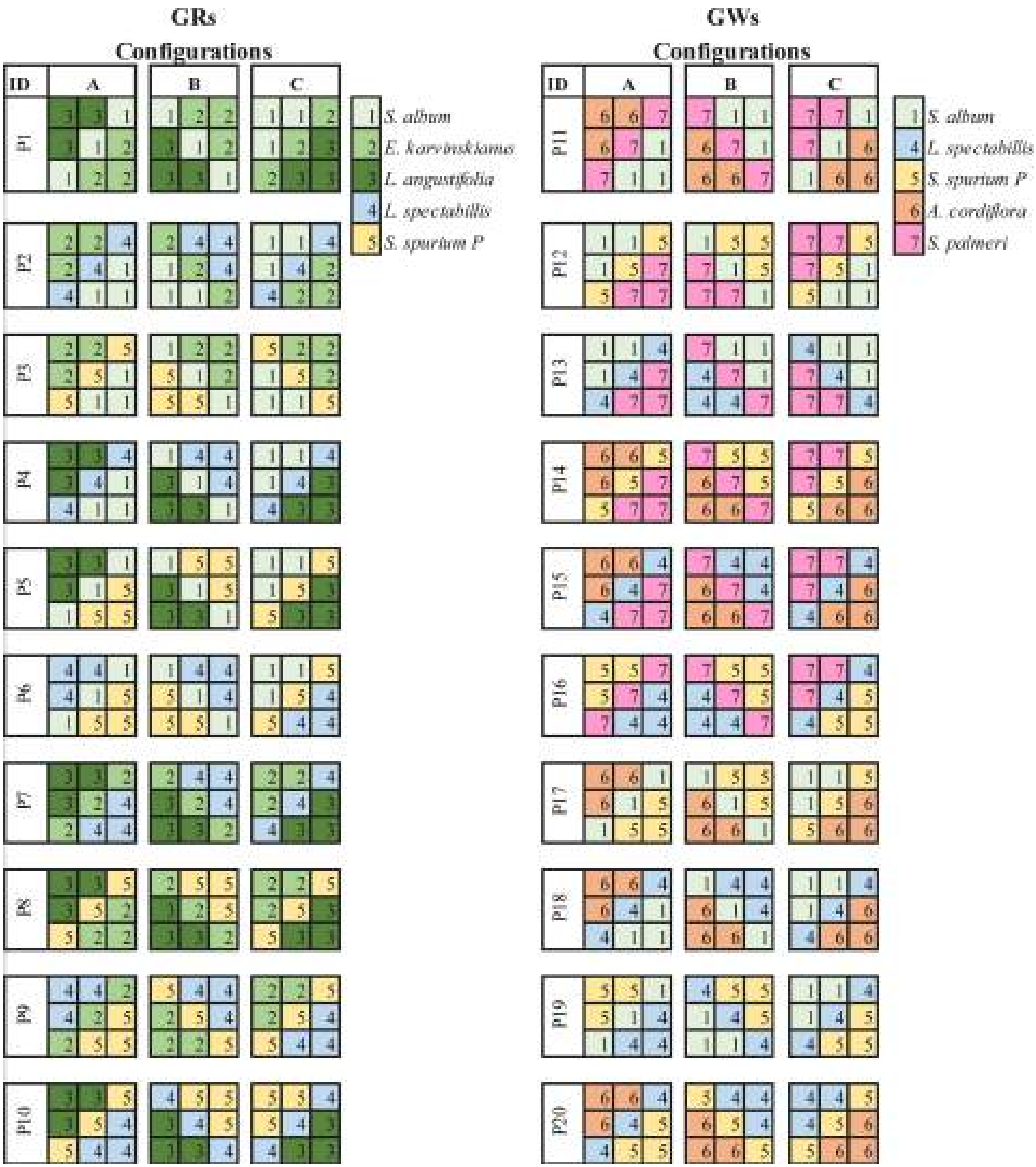

Fig. 1. Configurations A, B and C for GR and GW polycultures. Numbers from 1 to 7 indicate species analyzed. P1 to P10 indicate polycultures for GR; P11 to P20 for GW.

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 Figs. 6 and 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. Results

3.1. Comparison of $PM_{2.5}$ captured by vegetation in monocultures and polycultures

Fig. 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.

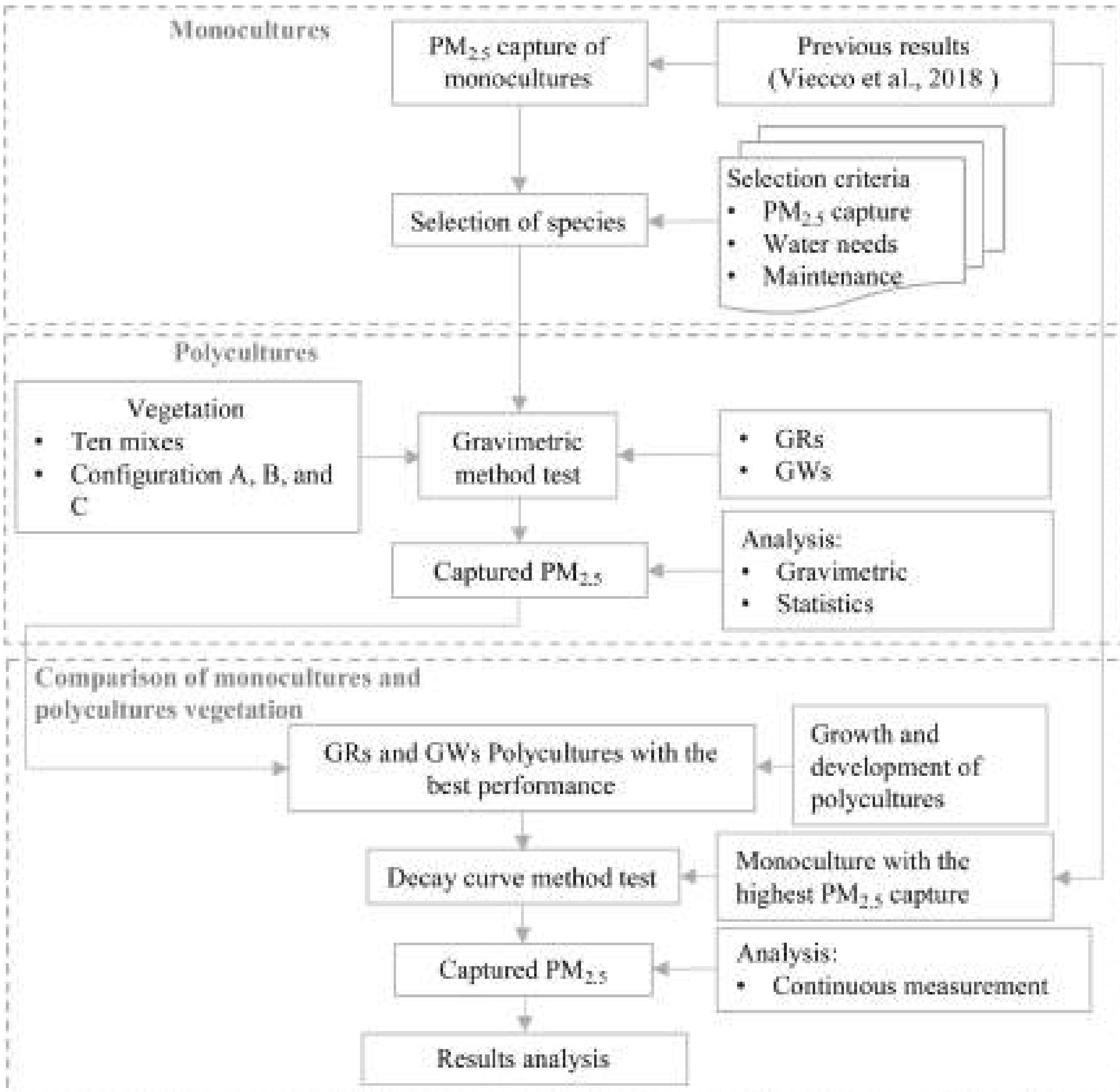

Fig. 2. Schematic representation of the experimental procedures.

Table 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 kW h m^{-2} day^{-1}	400 W Sodium Light
Vegetation cover	5 m^2	NA
Powdered incense	0.34 g (Combustion temperature: 300 °C)	Heating plate

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. 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. 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. 5 shows a comparison between *S. album*, *L. spectabillis*, and *S. spurium P* with respect to $PM_{2.5}$ capture, as both GR and GW polycultures.

Table 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, and P16
7 and 8	GWs	P17, P18, P19, P20, P11, and P12

* Each polyculture includes the three spatial configurations (A, B, C) in Fig. 1.

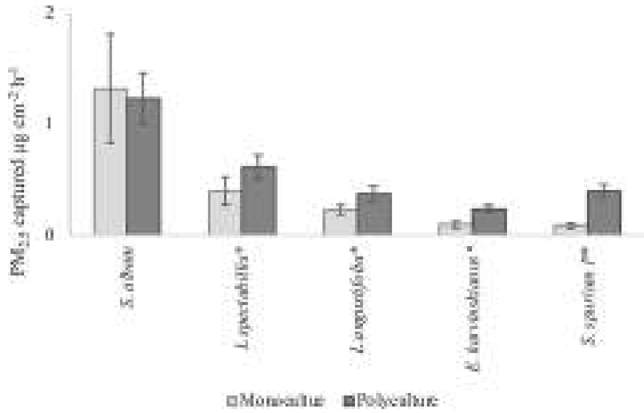

Fig. 3. $PM_{2.5}$ captured by the GR vegetation in monocultures and polycultures. Species marked with (*) showed statistically significant differences between monocultures and polycultures with 95 % of confidence ($p < 0.05$).

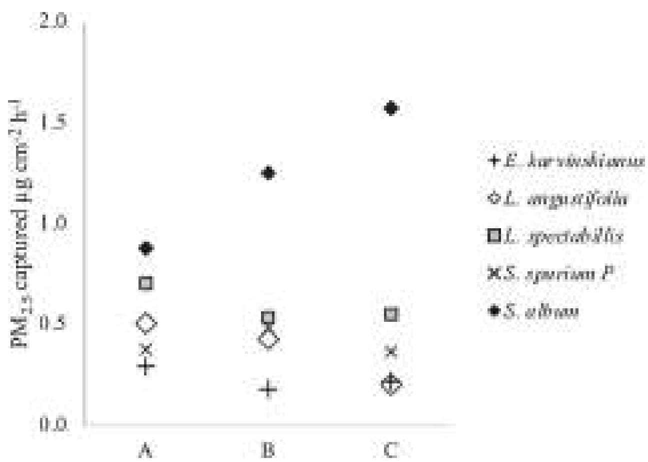

Fig. 4. Mean $PM_{2.5}$ captured by the GR vegetation in polycultures with respect to the configurations: A, B, or C.

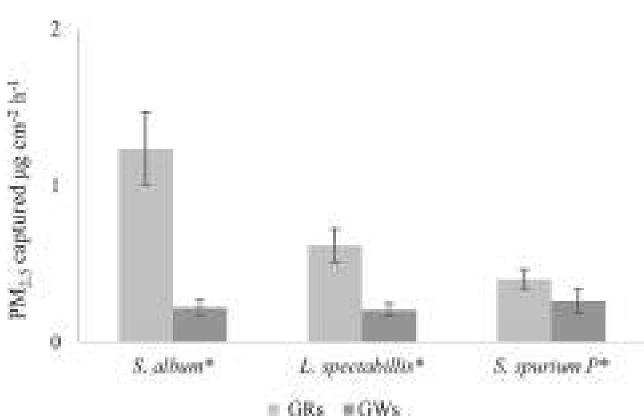

Fig. 5. Mean $PM_{2.5}$ captured by the three species as GR and GW polycultures. Species marked with (*) showed statistically significant differences between GRs and GWs vegetation with 95 % of confidence ($p < 0.05$).

3.2. $PM_{2.5}$ capture in polycultures

With respect to GR and GW polycultures, statistically significant differences were observed between $PM_{2.5}$ capture of different species. Two groups of GR polycultures were identified with (a) high and (b) low levels of $PM_{2.5}$ capture (Fig. 6). The average $PM_{2.5}$ capture by the

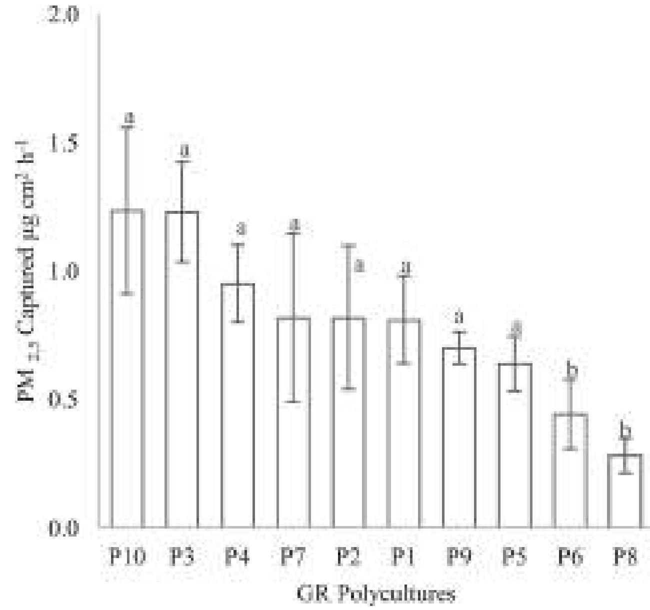

Fig. 6. Mean $PM_{2.5}$ captured by the polycultures in GRs under laboratory conditions. Letters ‘a’ and ‘b’ are used to show significant differences among polycultures ($p < 0.05$).

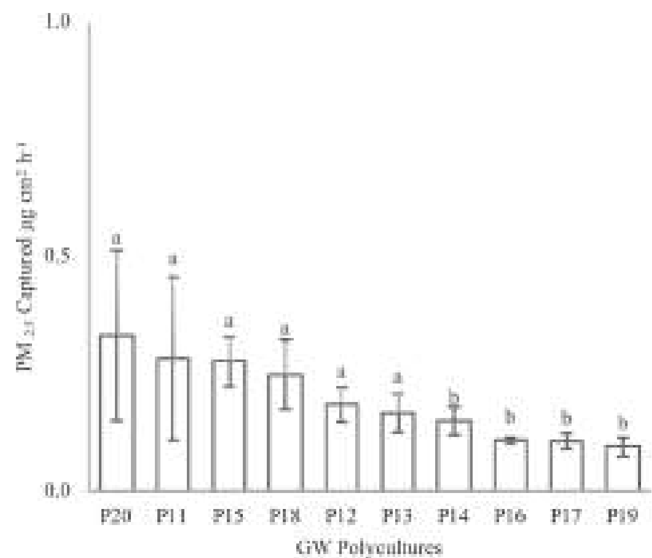

Fig. 7. Mean $PM_{2.5}$ captured by the polycultures in GWs under laboratory conditions. Letters ‘a’ and ‘b’ are used to show significant differences among polycultures ($p < 0.05$).

polycultures was between 0.3 µg cm^{-2} h^{-1} and 1.2 µg cm^{-2} h^{-1}. Likewise, two groups of GW polycultures were also identified by their levels of $PM_{2.5}$ capture (Fig. 7).

3.3. Decay curve test of monocultures and polycultures

Fig. 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*

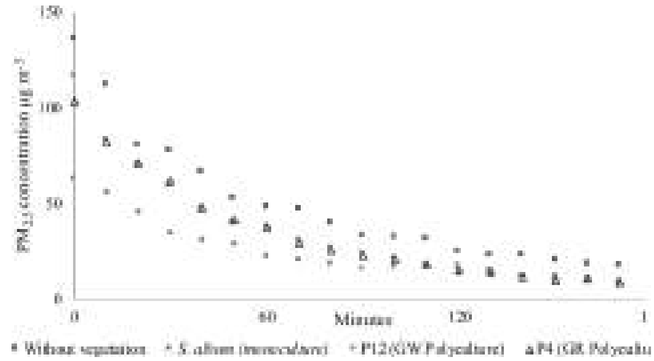

Fig. 8. Decay curve of $PM_{2.5}$ concentration inside the test-module with *S. album* (monoculture), P4 and P12 (polycultures), and without vegetation.

monoculture; the decay rate λ was significantly higher in P4 and P12 (Table 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.

4. Discussion

In these experiments, we investigated the impact of biodiversity on the ability to capture $PM_{2.5}$ from GRs and GWs using two methods. 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 (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 GR and GW polycultures effectively reduce $PM_{2.5}$ concentration, thus they have the potential of 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 (without vegetation).

Table 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

λ is the decay rate in table.

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 GR and GW 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.

Author Contributions

M.V., H.J., and S.V. conceived and designed the experiments; M.V. carried out the experiments; all authors analyzed the data and wrote the paper.

Declaration of Competing Interest

The authors report no declarations of interest.

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References

Abhijith, K.V., Kumar, P., Gallagher, J., McNabola, A., Baldauf, R., Pilla, F., Broderick, B., Di Sabatino, S., Pulvirenti, B., 2017. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – a review. Atmos. Environ. 162, 71–86. https://doi.org/10.1016/j.atmosenv.2017.05.014.

Alexandri, E., Jones, P., 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Build. Environ. 43, 480–493.

Barraza, F., Lambert, F., Jorquera, H., Villalobos, A.M., Gallardo Klenner, L., 2017. Temporal Evolution of Main Ambient PM2. 5 Sources in Santiago, chile, From 1998 to 2012.

Berndtsson, J.C., 2010. Green roof performance towards management of runoff water quantity and quality: a review. Ecol. Eng. 36, 351–360.

Besir, A.B., Cuce, E., 2018. Green roofs and facades: a comprehensive review. Renew. Sustain. Energy Rev. 82, 915–939. https://doi.org/10.1016/j.rser.2017.09.106.

Bracken, M.E.S., Stachowicz, J.J., 2006. Seaweed diversity enhances nitrogen uptake via complementary use of nitrate and ammonium. Ecology. 87, 2397–2403.

Brenneisen, S., 2003. The Benefits of Biodiversity From Green Roofs ∝ Key Design Consequences.

Burnett, R., Chen, H., Szyszkowicz, M., Fann, N., Hubbell, B., Pope, C.A., Apte, J.S., Brauer, M., Cohen, A., Weichenthal, S., Coggins, J., Di, Q., Brunekreef, B., Frostad, J., Lim, S.S., Kan, H., Walker, K.D., Thurston, G.D., Hayes, R.B., Lim, C.C., Turner, M.C., Jerrett, M., Krewski, D., Gapstur, S.M., Diver, W.R., Ostro, B., Goldberg, D., Crouse, D.L., Martin, R.V., Peters, P., Pinault, L., Tjepkema, M., van Donkelaar, A., Villeneuve, P.J., Miller, A.B., Yin, P., Zhou, M., Wang, L., Janssen, N. A.H., Marra, M., Atkinson, R.W., Tsang, H., Quoc Thach, T., Cannon, J.B., Allen, R. T., Hart, J.E., Laden, F., Cesaroni, G., Forastiere, F., Weinmayr, G., Jaensch, A., Nagel, G., Concin, H., Spadaro, J.V., 2018. Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. Proc. Natl. Acad. Sci. U. S.A. 115, 9592 LP–LP 9597. https://doi.org/10.1073/pnas.1803222115.

Cabaraban, M.T.I., Kroll, C.N., Hirabayashi, S., Nowak, D.J., 2013. Modeling of air pollutant removal by dry deposition to urban trees using a WRF/CMAQ/i-Tree Eco coupled system. Environ. Pollut. 176, 123–133. https://doi.org/10.1016/j.envpol.2013.01.006.

Cardinale, B.J., 2011. Biodiversity improves water quality through niche partitioning. Nature. 472, 86–89.

Chow, J.C., Watson, J.G., Mauderly, J.L., Costa, D.L., Wyzga, R.E., Vedal, S., Hidy, G.M., Altshuler, S.L., Marrack, D., Heuss, J.M., Wolff, G.T., Pope, C.A., Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. J. Air Waste Manag. Assoc. 56, 1368–1380. https://doi.org/10.1080/10473289.2006.10464545.

Cook-Patton, S.C., Bauerle, T.L., 2012. Potential benefits of plant diversity on vegetated roofs: a literature review. J. Environ. Manage. 106, 85–92. https://doi.org/10.1016/j.jenvman.2012.04.003.

Coronel-Brizio, H.F., Hernández-Montoya, A.R., Jiménez-Montaño, M.A., Mora-Forsbach, L.E., 2007. Una prueba empírica de generadores de números pseudoaleatorios mediante un proceso de decaimiento exponencial. Rev. Mex. Fis. 53, 350–357.

Dunnett, N., Nagase, A., Booth, R., Grime, P., 2008. Influence of vegetation composition on runoff in two simulated green roof experiments. Urban Ecosyst. 11, 385–398.

Dzierżanowski, K., Popek, R., Gawrońska, H., Sæbø, A., Gawroński, S.W., 2011. Deposition of particulate matter of different size fractions on leaf surfaces and in waxes of urban forest species. Int. J. Phytoremediation 13, 1037–1046. https://doi.org/10.1080/15226514.2011.552929.

Fuller, R.A., Irvine, K.N., Devine-Wright, P., Warren, P.H., Gaston, K.J., 2007. Psychological benefits of greenspace increase with biodiversity. Biol. Lett. 3, 390–394.

Hamanaka, R.B., Mutlu, G.M., 2018. Particulate matter air pollution: effects on the cardiovascular system. Front. Endocrinol. (Lausanne). 9, 680. https://www.frontiersin.org/article/10.3389/fendo.2018.00680.

Isbell, F., Adler, P.R., Eisenhauer, N., Fornara, D., Kimmel, K., Kremen, C., Letourneau, D. K., Liebman, M., Polley, H.W., Quijas, S., 2017. Benefits of increasing plant diversity in sustainable agroecosystems. J. Ecol. 105, 871–879.

Jayasooriya, V.M., Ng, A.W.M., Muthukumaran, S., Perera, B.J.C., 2017. Green infrastructure practices for improvement of urban air quality. Urban For. Urban Green. 21, 34–47. https://doi.org/10.1016/j.ufug.2016.11.007.

Jeanjean, A., Buccolieri, R., Eddy, J., Monks, P., Leigh, R., 2017. Air quality affected by trees in real street canyons: the case of Marylebone neighbourhood in central London. Urban For. Urban Green. 22, 41–53. https://doi.org/10.1016/j.ufug.2017.01.009.

Kiær, L.P., Skovgaard, I.M., Østergård, H., 2009. Grain yield increase in cereal variety mixtures: a meta-analysis of field trials. F. Crop. Res. 114, 361–373.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated. Meteorol. Zeitschrift. 15, 259–263. https://doi.org/10.1127/0941-2948/2006/0130.

Kumar, R., Kaushik, S.C., 2005. Performance evaluation of green roof and shading for thermal protection of buildings. Build. Environ. 40, 1505–1511.

Lundholm, J., MacIvor, J.S., MacDougall, Z., Ranalli, M., 2010. Plant species and functional group combinations affect green roof ecosystem functions. PLoS One 5.

Mejía, P., 2007. Diseño De Parque Municipal En Santa Cruz De Los Cáñamos. https://previa.uclm.es/area/ing_rural/Proyectos/PedroJoseDeLosAngeles/01_Memoria.pdf.

Menz, M.H.M., Phillips, R.D., Winfree, R., Kremen, C., Aizen, M.A., Johnson, S.D., Dixon, K.W., 2011. Reconnecting plants and pollinators: challenges in the restoration of pollination mutualisms. Trends Plant Sci. 16, 4–12.

Mohajeri, N., Gudmundsson, A., Scartezzini, J., 2015. Expansion and densification of cities: linking urban form to urban ecology. Int. Conf. Futur. Build. Dist. Sustain. From Nano to Urban Scale 475–480.

Nagase, A., Dunnett, N., 2010. Drought tolerance in different vegetation types for extensive green roofs: effects of watering and diversity. Landsc. Urban Plan. 97, 318–327.

Ottel, M., van Bohemen, H.D., Fraaij, A.L.A., 2010. Quantifying the deposition of particulate matter on climber vegetation on living walls. Ecol. Eng. 36, 154–162. https://doi.org/10.1016/j.ecoleng.2009.02.007.

Pope, C.A., Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. J. Air Waste Manage. Assoc. 56, 709–742. https://doi.org/10.1080/10473289.2006.10464485.

Rixen, C., Mulder, C.P.H., 2005. Improved water retention links high species richness with increased productivity in arctic tundra moss communities. Oecologia. 146, 287–299.

Sandoval, V., Bonilla, C.A., Gironás, J., Vera, S., Victorero, F., Bustamante, W., Rojas, V., Leiva, E., Pastén, P., Suárez, F., 2017. Porous media characterization to simulate water and heat transport through green roof substrates. Vadose Zone J. 16, 1–14.

Upadhyaya, M.K., Blackshaw, R.E., 2007. Non-chemical Weed Management: Principles, Concepts and Technology. Cabi.

Vera, S., Pinto, C., Tabares-Velasco, P.C., Bustamante, W., Victorero, F., Gironás, J., Bonilla, C.A., 2017. Influence of vegetation, substrate, and thermal insulation of an extensive vegetated roof on the thermal performance of retail stores in semiarid and marine climates. Energy Build. 146, 312–321. https://doi.org/10.1016/j.enbuild.2017.04.037.

Verheyen, K., Bulteel, H., Palmborg, C., Olivié, B., Nijs, I., Raes, D., Muys, B., 2008. Can complementarity in water use help to explain diversity–productivity relationships in experimental grassland plots? Oecologia. 156, 351–361.

Viecco, M., Vera, S., Jorquera, H., Bustamante, W., Gironás, J., Dobbs, C., Leiva, E., 2018. Potential of particle matter dry deposition on green roofs and living walls vegetation for mitigating urban atmospheric pollution in semiarid climates. Sustainability. 10, 2431. https://doi.org/10.3390/su10072431.

Wania, A., Bruse, M., Blond, N., Weber, C., 2012. Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations. J. Environ. Manage. 94, 91–101. https://doi.org/10.1016/j.jenvman.2011.06.036.

Weyens, N., Thijs, S., Popek, R., Witters, N., Przybysz, A., Espenshade, J., Gawronska, H., Vangronsveld, J., Gawronski, S.W., 2015. The role of plant microbe interactions and their exploitation for phytoremediation of air pollutants. Int. J. Mol. Sci. 16, 25576–25604. https://doi.org/10.3390/ijms161025576.

WHO, 2016. Public Health, Environmental and Social Determinants of Health (PHE). https://www.who.int/phe/health_topics/outdoorair/databases/cities/en/.

WHO, 2021. Air Quality and Health. https://www.who.int/teams/environment-climate-change-and-health/air-quality-and-health.

Yang, J., Yu, Q., Gong, P., 2008. Quantifying air pollution removal by green roofs in Chicago. Atmos. Environ. 42, 7266–7273. https://doi.org/10.1016/j.atmosenv.2008.07.003.

Yang, J., Wang, H., Xie, B., 2015. Accumulation of particulate matter on leaves of nine urban greening plant species with different micromorphological structures in Beijing. Research of Environmental Sciences 28, 13198. https://doi.org/10.13198/j.issn.1001-6929.2015.03.08.

Zhang, W., Liu, G., Sun, J., Fornara, D., Zhang, L., Zhang, F., Li, L., 2017. Temporal dynamics of nutrient uptake by neighbouring plant species: evidence from intercropping. Funct. Ecol. 31, 469–479.