The influence of plant species, leaf morphology, height and season on PM capture efficiency in living wall systems

1   # The influence of plant species, leaf morphology, height and season on PM

2   capture efficiency in living wall systems

3

4   ## Abstract

5   Green infrastructure (GI) is already known to be a suitable way to enhance air quality in urban

6   environments. Living wall systems (LWS) can be implemented in locations where other forms of GI, such

7   as trees or hedges, are not suitable. However, much debate remains about the variables that influence

8   their particulate matter (PM) accumulation efficiency. This study attempts to clarify which plant species

9   are relatively the most efficient in capturing PM and which traits are decisive when it comes to the

10   implementation of a LWS. We investigated 11 plant species commonly used on living walls, located close

11   to train tracks and roads. PM accumulation on leaves was quantified by magnetic analysis (*Saturation*

12   *Isothermal Remanent Magnetization* (SIRM)). Several leaf morphological variables that could potentially

13   influence PM capture were assessed, as well as the Wall Leaf Area Index. A wide range in SIRM values (2.74

14   - 417 µA) was found between all species. Differences in SIRM could be attributed to one of the

15   morphological parameters, namely SLA (specific leaf area). This suggest that by just assessing SLA, one can

16   estimate the PM capture efficiency of a plant species, which is extremely interesting for urban greeners.

17   Regarding temporal variation, some species accumulated PM over the growing season, while others

18   actually decreased in PM levels. This decrease can be attributed to rapid leaf expansion and variations in

19   meteorology. Correct assessment of leaf age is important here; we suggest individual labeling of leaves for

20   further studies. Highest SIRM values were found close to ground level. This suggests that, when traffic is

21   the main pollution source, it is most effective when LWS are applied at ground level. We conclude that

22 LWS can act as local sinks for PM, provided that species are selected correctly and systems are applied

23 according to the state of the art.

24

1   Introduction

26 Particulate matter (PM) pollution is one of the major challenges in urban environments nowadays. Even

27 though $PM_{2.5}$ concentrations in urban environments decreased by approximately 20% between 2005 and

28 2015, EU air quality standards have not been met (EEA, 2017a; EEA, 2017b). Epidemiological studies show

29 a strong correlation between PM pollution and adverse health effects (Pope III and Dockery 2006; Solomon

30 et al. 2012; Van Dyck et al. 2019). Besides severe health effects and premature mortality (Brunekreef

31 1997), PM pollution also causes damage to the environment, crops and infrastructure (Jimoda et al. 2012;

32 Rai et al. 2016).

33 Urban green infrastructure (UGI) such as trees, hedgerows, green roofs and green walls can act as a natural

34 filter for PM and contribute to air pollution mitigation by deposition of particles on plant leaves (Beckett,

35 Freer-Smith, and Taylor 1998; Litschke and Kuttler 2008; Nowak, Crane, and Stevens 2006; Pugh et al.

36 2012; Shao et al. 2021). Deposition effects related to vegetation were studied by Gallagher et al. (2015)

37 and Janhäll (2015), among others. Moreover, Abhijith et al. (2017) discussed the comparison of different

38 UGIs on air quality improvement. However, due to the *street canyon* effect, models suggest that trees can

39 sometimes have a negative impact on local air quality (Vos et al. 2012) by hampering air flow. In contrast,

40 green walls (vertical structures covered by vegetation) do not inhibit free air flow through the street

41 canyon and thus can also have a positive impact on urban air quality, when applied appropriately.

42 Moreover, green walls provide many more ecosystem services than PM mitigation, such as cooling the

43 ambient air and underlying walls (Pérez et al. 2011; Wong et al. 2010; Koch et al. 2020), increasing

44 biodiversity (Madre et al. 2015), water retention and purification (Prodanovic et al. 2017; van de Wouw et

45 al. 2017; Hussain Lakho et al. 2021), carbon sequestration (Tallis et al. 2015) and social and cultural benefits

46 (White and Gatersleben 2011).

47 Recently, some interesting studies have been published regarding green walls and their potential to

48 capture PM, on which a review was published by Ysebaert et al. (2021). Literature mainly considered soil-

49 bound Ivy (*Hedera helix*) (Ottelé et al. 2010; Sternberg et al. 2010; Przybysz et al. 2014), although (Perini

50 et al. 2017) studied several other climber plant species and (Weerakkody et al. 2017, 2018a, 2018b and

51 Viecco et al. 2018) reported about living wall systems (LWS). LWS are systems in which plants that normally

52 grow in the soil are rooted in a substrate material, directly attached to the wall (Koch et al. 2020). The

53 substrate can be pre-cultivated panels, bags, textiles or other materials, and can be of natural composition

54 (soil, moss) or synthetic. There is always an irrigation system that also includes nutrient distribution over

55 the plants. This kind of system facilitates the use of a wide variety of plant species, from small herbs to

56 medium sized shrubs.

57 Plant species, all of which have their own unique morphological and physiological characteristics, are

58 typically characterized by different PM capture qualities according to this review paper. The importance

59 of selecting plants with certain traits is also highlighted by Litschke and Kuttler (2008), Weerakkody et al.

60 (2017), Muhammad et al. (2019) and others. It was found that plant leaves with a higher wax content

61 (Perini et al. 2017), higher wettability (Muhammad et al. 2019; Wang et al. 2013) or with a higher stomatal

62 density (Weerakkody et al. 2018b) collect more particles. The influence of trichomes is still considered

63 inconclusive for green wall studies. Hairy leaves were less effective in PM capture according to Perini et al.

64 (2017) while hairiness was considered insignificant according to Weerakkody et al. 2018b). This is in

65 contrast to other studies on more than hundred tree, shrub and climber species (Sæbø et al. 2012; Kardel

66 et al. 2012; Muhammad et al. 2019) and herbaceous plants (Weber et al; 2014), which report important

67 differences between hairy and non-hairy leaves and significant positive relationships between PM

68   accumulation and trichome density. To summarize, we assume that the amount of LWS species considered

69   is too small to make decent comparisons with the large amount of tree species considered in literature.

70   Leaf shape was also considered an important variable, with small and needle-like leaves being better PM

71   accumulators (Beckett et al. 2000; Dzierzanowski et al. 2011). The specific leaf area (SLA, the amount of

72   one-sided leaf surface divided by its dry mass) appears to be a good predictor of PM accumulation and

73   immobilisation for trees, as a proxy for the complex interactions of various leaf morphological

74   characteristics (Muhammad 2019, 2020). In contrast, a recent study conducted by Paull et al. (2019) on

75   11 common green wall plant species found minimal evidence for the influence of leaf morphology on PM

76   accumulation, but nevertheless reported differences between species.

77   Pollution level is another important factor to be considered. Several studies suggest that the load of

78   captured particles on the leaves is higher when the pollution level is higher (Ottelé et al. 2010; Sternberg

79   et al. 2010; Kardel et al. 2012; Przybysz et al. 2014). In our study, however, pollution level is constant due

80   to the nature of the experimental setup; a common garden with similar outdoor conditions and sources,

81   which implies that differences between species can be attributed to other parameters. Also wind speed,

82   turbulence, relative air humidity and precipitation can influence particle deposition and accumulation on

83   plants (Litschke and Kuttler 2008; Weerakkody, John W Dover, et al. 2018).

84   For living wall systems (LWS) in particular, insufficient research has been conducted in terms of their PM

85   mitigation capacity, and the few studies conducted have produced inconsistent results concerning

86   relevant parameters. Furthermore, the effects of height on PM deposition are generally poorly understood

87   due to the lack of studies. However, green walls offer the opportunity to capture PM at lower heights than

88   urban trees, e.g. they can be applied at pedestrian height, while tree canopies are situated higher above

89   the ground. Furthermore, the seasonal dynamics and height variation of PM accumulation on leaves in

90   LWS were studied.

91   In this study, it is examined to which extent PM accumulation on plants in LWS is determined by plant

92   species and their leaf characteristics, utilizing biomagnetic analysis (SIRM; *Saturation Isothermal*

93   *Remanent Magnetization*) (Hofman et al. 2013; Matzka and Maher 1999). We aim to provide suggestions

94   to optimize the design of living wall systems in terms of plant species selection to maximise PM mitigation.

95   Moreover, the influence planting height on PM load and seasonal variation within these plant species are

96   included in the analysis. We hypothesize that smaller, hairier leaves with lower SLA and at lower height

97   perform better in terms of PM accumulation capacity. Furthermore we expect an increase in PM load on

98   the plants over the growing season.

99

2   Materials & methods

2.1   Test location

102   Plant samples were collected at the Testing Center for Floriculture (Proefcentum voor Sierteelt, hereafter

103   referred to as PCS) in Destelbergen, Belgium (lat. = 51.071744° N, lon. = 3.812062° E) (Appendix Figure 1).

104   This site has a large amount of LWS which are all exposed to the same external conditions. Local pollution

105   sources originated from the background concentrations of the city of Ghent, the Port of Ghent and the

106   steel manufacturer Arcelor-Mittal, located west of the test site. The impact of the Arcelor-Mittal

107   metallurgic factory on airborne pollution was discussed by (Declercq et al. 2020) Considering the main

108   southwest wind direction in Belgium, the test site is located more or less downwind of these urban sources.

109   Furthermore, a calm street and a railroad are located in close proximity of the test site; approximately 10

110   m westward and 100 m northward, respectively. The busy ring road R4 is located approximately 400 m

111   west of the test area.

112

2.2   Sample collection

The test facility contains 13 southwest-facing living wall systems (LWS, wall-ID 1-13), constructed in 2016 and developed by different manufacturers from Belgium and the Netherlands (Appendix Figure 2). The LWS contained a wide variety of plant species, an overview of which is given in Appendix table 1. A total of 11 species were sampled and only species that were sufficiently present for sampling without visibly damaging the system were selected for the experiment. However, not every plant species was present on each testing wall and some testing walls (wall 1 to 5 and 11) were removed during the experiment (Appendix table 2). Samples were collected in spring (28/04, sampling moment 1) and summer (24/08, sampling moment 2) of 2017 and spring (20/03, sampling moment 3) of 2018.

Since individual plants had been present for a year at the time of first sampling, environmental pollution level was equal for all systems (common garden) and the plants had developed fresh leaves since then, so that differences in plant origin were considered negligible. For magnetic analysis, from each species 4 to 10 healthy leaves (depending on the availability and to have a sufficient leaf area for testing) were collected at three different heights: (2.5 ± 0.2) m (A), (1.5± 0.2) m (B) and (0.5 ± 0.2) m (C). In order to avoid contamination, the leaves were put into paper bags immediately after cutting and stored at 7°C for up to maximum 48 hours before further analysis in the lab.

2.3   Meteorological conditions

Meteorological data for the entire sampling period and four extra months before were obtained from the Flanders Environmental Agency (VMM) for the nearby station M701 at Tolhuiskaai, Gent. Appendix Figure 3 shows that temperatures never fell below -5°C and never rose above 27°C. According to Köppen Climate Classification, our study area is situated in zone Cfb which is a temperate oceanic climate.

2.4   Leaf morphological variables

137   All leaf analyses were performed in the Laboratory of Environmental and Urban Ecology of the Bioscience

138   Engineering Department of the University of Antwerp, Belgium. For each species considered, a series of

139   leaf morphological variables was determined with the aim of determining key characteristics for PM

140   capture. This was done at one sampling moment, taking only mature leaves into account. A set of

141   morphological parameters were determined for 5 leaves per species (Appendix table 4) unless mentioned

142   otherwise.

143   The *drop contact angle* (DCA, degrees) describes the internal angle between the perimeter of a water

144   droplet and the leaf contact surface, and is a measure for the hydrophobicity of the leaf (Muhammad et

145   al. 2020). Leaves with a higher DCA have a higher hydrophobicity and are less wettable. To assess this

146   variable, ~~two~~ fresh leaves collected on the same day and treated within 6 hours of harvesting were used.

147   The studied leaf was cut in half and the two parts were fixed to a surface with either the adaxial or the

148   abaxial leaf side facing upwards using double-sided tape. A 7.5 μL droplet of distilled water was put on

149   both the adaxial and abaxial side of a leaf. A picture was taken with a Canon EOS 550D camera with a

150   macro lens (MP-E 65 mm 1:2.8) with 3× magnification. For image processing, the software ImageJ was

151   used with the plugin 'Low-Bond Axisymmetric Drop Shape Analysis' (LB-ADSA) (Stalder et al. 2010)(Stalder

152   et al. 2010) to determine the mean of the left and right drop contact angles. Some examples of different

153   DCA's are shown in Appendix Figure 4.

154   The *specific leaf area* (SLA, m² kg^{-1}) is the ratio between the one-sided fresh leaf area (A_{leaf}) and the leaf

155   dry mass (M_{leaf}). For this, 10 fresh leaves per plant species were scanned maximum 24 hours after sampling

156   with an HP Scanjet G3100 scanner and leaf area was measured in ImageJ. Dry mass of the leaves was

157   measured with an analytical balance (S-234, Denver Instruments, NY, USA, accuracy= 0.1 mg), after drying

158   for at least 160h at 40°C.

$$Specific\ leaf\ area\ (SLA) = \frac{A_{leaf}}{M_{leaf}}$$

159

160   The *leaf dissection index* (LDI, dimensionless)) describes leaf shape and is the ratio of the leaf

161   circumference (P_{leaf}) to the root of the leaf area ($\sqrt{A_{leaf}}$) (McLellan and Endler 1998). The lowest value is

162   3.545 which is for a circular leaf, while a high LDI means long or serrated leaf shape (Koch, Samson, and

163   Denys 2019). For species with compound leaves, LDI is taken for one leaflet only.

$$Leaf\ dissection\ index\ (LDI) = \frac{P_{leaf}}{\sqrt{A_{leaf}}}$$

164

165   The *functional leaf size* (FLS) is determined by dividing the largest circular area in the leaf (A_{circle}) by the

166   leaf area (A_{leaf}). This is a good measure for leaf boundary layer size, which is an important factor for PM

167   deposition (Koch et al. 2019, 2020). For species with compound leaves, FLS is taken for one leaflet instead

168   of the whole leaf as we assume this is aerodynamically more correct.

$$Functional\ leaf\ size\ (FLS) = \frac{A_{circle}}{A_{leaf}}$$

169

170   Finally, *hairiness* of leaves was determined by visual examination of the DCA images. Three classes were

171   determined: no visible hairs (0), visually short hairs (1) and visually long hairs (2) (Appendix Figure 4) as

172   viewed through the macro lens. This was based on the amount and the length of trichomes.

173

174   2.5   Magnetic analysis

175   PM accumulation on leaves was assessed using biomagnetic analysis as described by (Kardel et al. 2011,

176   2012; Hofman et al. 2014a, b). Hofman et al. (2017) published a review covering all knowledge upon the

177   publication date about PM deposition on biological surfaces. In this method, dried leaves were first tightly

178   wrapped in cling film and placed in small plastic containers of 10 cm³. Next, the leaf samples were

179 magnetized (*Molspin pulse* magnetiser) in a magnetic field of 800 mT and the remanent magnetisation (in

180 A/m) was measured in a *Molspin Minispin* magnetometer. In this way, the SIRM (*saturation isothermal*

181 *remanent magnetisation*) was determined by multiplying the volume of the container for the remanent

182 magnetization and normalizing for leaf area or mass. This variable is an indicator of atmospheric traffic-

183 and industry-related particulate matter and metals (Kardel et al. 2012; Maher et al. 2013). The SIRM values

184 were normalized both for mass (SIRMm, $A \cdot m^2 \cdot kg^{-1} \cdot 10^6$), measured with a scientific balance (S-234,

185 Denver Instruments, NY, USA, accuracy= 0.1 mg) and for fresh leaf area (SIRMa, μA) which was determined

186 with a Li-3100 leaf area meter (Li-cor Inc., Lincoln, NE, USA). In total, 578 leaf samples were magnetically

187 analyzed.

188

189 2.6   Wall Leaf Area Index and upscaling

190 The *wall leaf area index* (WLAI) is a dimensionless number that describes the amount of one sided leaf

191 area compared to the amount of covered wall surface (Koch, et al. 2020; Ysebaert et al. 2021). Often the

192 *leaf area index* is used to describe tree canopy cover, but for vertical green elements, the leaf area index

193 has been expanded to the wall leaf area index. This is an important parameter, as it can be used to calculate

194 the total amount of PM capture per unit wall surface covered by LWS, and is calculated as:

195 $$\text{WLAI} = \frac{leaf\ surface\ (m^2)}{wall\ surface\ (m^2)}$$

196 To assess this parameter, for every plant species a 50x50 cm square was cut out of one of the experimental

197 green walls. This was done during the pruning season in August. Leaf areas were determined for fresh

198 leaves.

199 SIRMa data provide information about how much magnetic particulate matter is accumulated on a certain

200 amount of leaf surface of a certain plant species (Hofman et al. 2014). But plant species themselves also

201   differ in how much leaf surface they actually have. Therefore, the SIRM was scaled up with WLAI to create

202   a variable called totalSIRM (total normalized SIRM), to give an idea of the total PM capture per unit of wall

203   surface area.

204 $$totalSIRM\ (\mu A) = SIRMa\ (\mu A) \times WLAI$$

205

206   ## 2.7   Statistical analysis

207   Data were analyzed in R version 3.3.1 (https://cran.r-project.org/). In this study, a difference is considered

208   significant if the p value is ≤ 0.05. Because of non-normality according to a Shapiro-Wilk normality test,

209   the SIRM data were ln transformed. A mixed model (lme) was used to test SIRM values against species,

210   sampling time, height and wall-ID (as a random factor). Some LWS have been analyzed more often than

211   others and because some species have been measured multiple times on the same LWS. This means that

212   SIRM values of species from the same wall can be expected to be more similar than on different walls,

213   because they are in a slightly different location. In order to know the significant differences in SIRMm and

214   SIRMa values between species, the order of species names in the model was changed until all

215   combinations were made. The same was done for the variables sampling time and height. Differences

216   between sampling times per species for both SIRM analyses regarding seasonal variation were retrieved

217   with ANOVA. Furthermore, correlations of all morphological parameters were tested against each other.

218   Because the morphological parameters were not taken from the same leaves as the SIRMm and SIRMa

219   values, the average SIRM values per plant species were tested with a linear model against all leaf

220   morphological parameters. Values that were almost significant were isolated and retested against SIRM

221   parameters.

222

## 3 Results

3.1 Difference in PM accumulation between species

The SIRM values per species normalized for mass (SIRMm), averaged for all sampling moments and all heights, ranged between 74.17 and 3543.22 $\mu A\ m^2\ kg^{-1}$ and are plotted in ascending order of log values in Figure 1. Figure 2 shows the surface area normalized SIRM (SIRMa) (values of 2.74 up to 417 μA). There were significant differences in SIRM signal between species, of which *Bergenia cordifolia* scored lowest for mass normalization while *Santolina chamaecyparissus* scored highest. *Santolina chamaecyparissus* also scored highest for area normalization, but *Campanula* sp. scored the lowest.
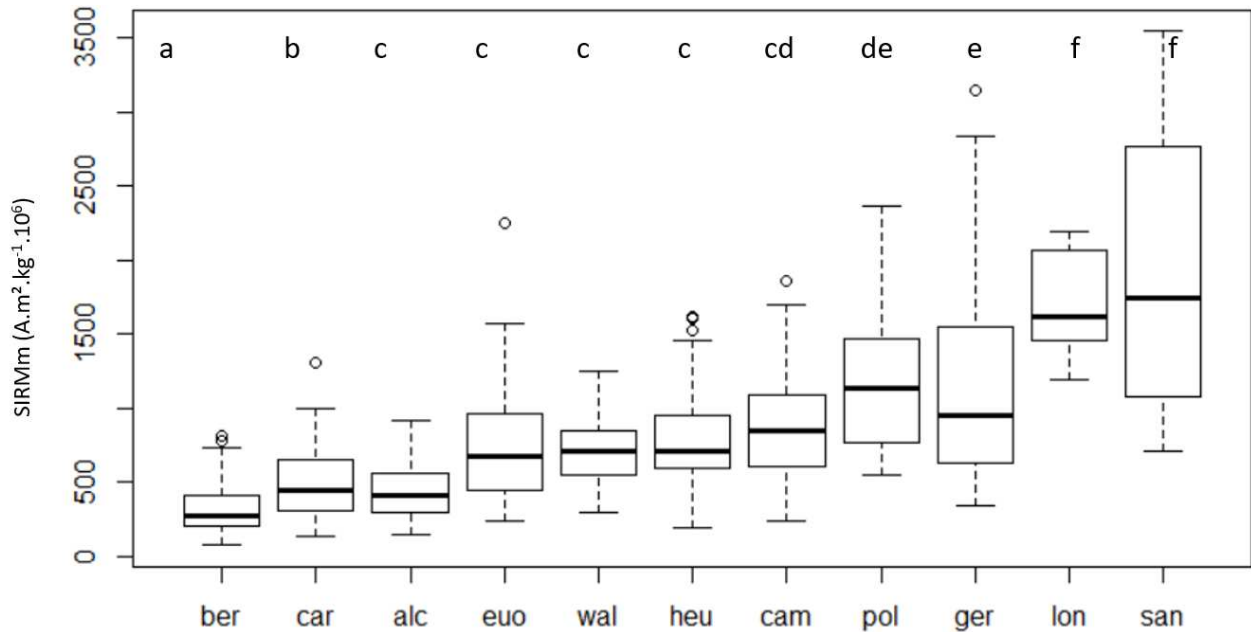
Figure 1: Boxplot of the leaf dry mass normalized SIRMm-values for all species, with indication of the mean, the first and third quartile, minimum and maximum values. Species abbreviations can be found in Appendix table 1. Species with different letters (a-f) are significantly ($p < 0.05$) different.
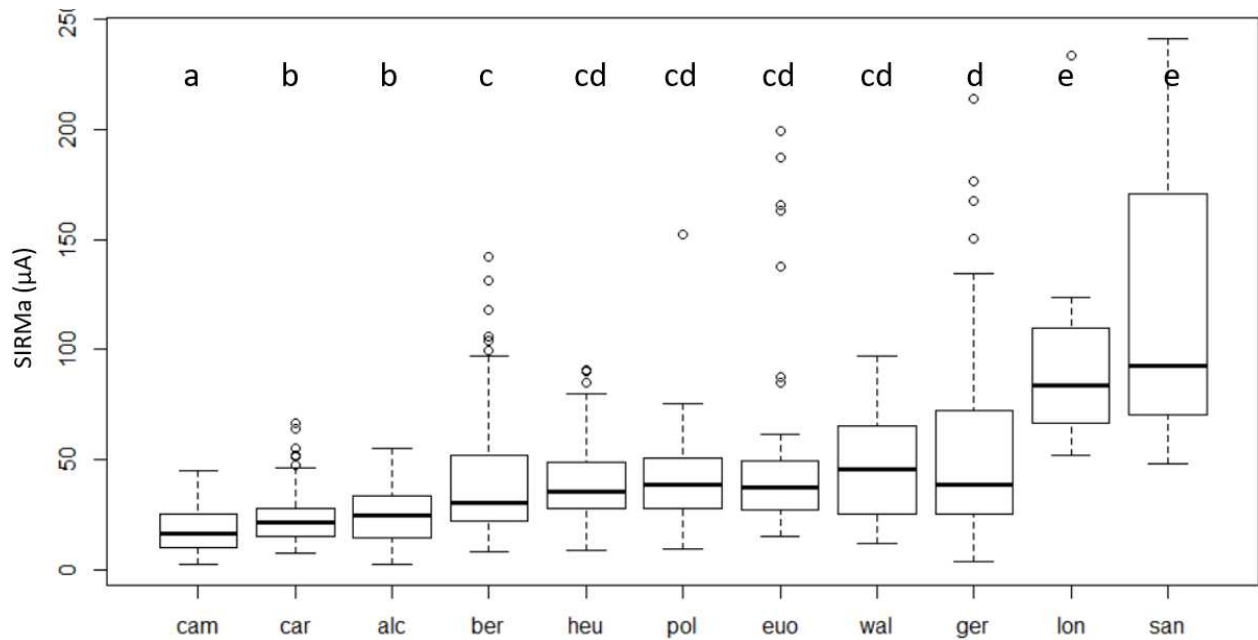
237

238 Figure 2: Boxplot of the leaf area normalized SIRMa-values for all species, with indication of the mean, the

239 first and third quartile, minimum and maximum values. Species abbreviations can be found in Appendix

240 table 1. Species with different letters (a-e) are significantly (p < 0.05) different.

241

242 3.2   TotalSIRM: average SIRMa normalized for WLAI

243 As mentioned earlier, in order to understand how much PM can be captured by a certain amount of foliage,

244 it is important to know how much leaf surface is available per unit of wall surface area. In order to obtain

245 comparable numbers, only SIRMa values of the first sampling campaign were considered, as this was the

246 sampling with the most samples of most species (see Appendix table 2). Figure 3 shows totalSIRM values

247 of species in ascending order.

248
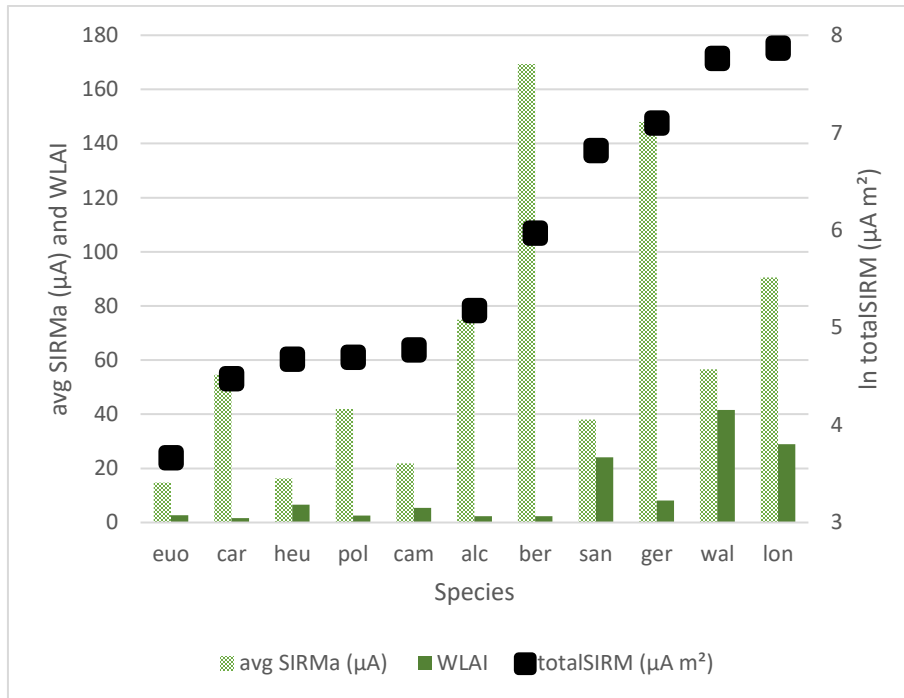
Figure 3: Total normalized ln transformed SIRM values (totalSIRM) of species in ascending order (right

axis). Average SIRMa and WLAI are both shown on the left axis. Species abbreviations can be found in

Appendix table 1.

3.3   Effect of sampling time – seasonal variation

When all species and heights are considered in the model, variation in SIRMm and SIRMa values can be

found between sampling moments (Fig. 4). For SIRMm, sampling 2 was significantly different from 1 and

3. For SIRMa, sampling time 3 was significantly different from the others.
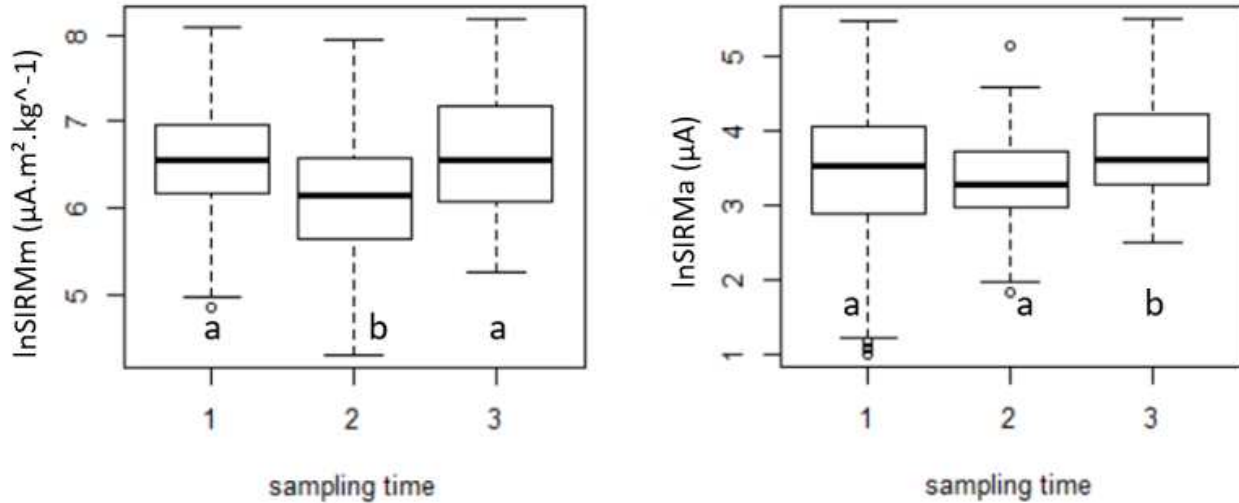
257

258 Figure 4: Boxplots of lnSIRMm values at the three sampling moments (1, 2 and 3). Values with different

259 letters (a-b) are significantly (p < 0.05) different.

260

261 Temporal patterns appear to be very different between species, both for SIRMm (Figure 5) and SIRMa

262 (Figure 6). We categorized these patterns into 2 categories. For *Alchemilla mollis* (SIRMm and SIRMa)*,*

263 *Campanula* sp. (SIRMa), *Geranium* sp. (SIRMa), *Heuchera* sp. (SIRMm), *Polypodium vulgare* (SIRMa) and

264 *Walsteinia ternata* (SIRMm and SIRMa), we observed a general increase of values in time, hereafter

265 referred to as Category 1. Furthermore, *Bergenia cordifolia* (SIRMm and SIRMa), *Campanula* sp. (SIRMm),

266 *Carex* sp. (SIRMm and SIRMa), *Euonymus fortunei* (SIRMm), *Geranium* sp. (SIRMm), *Heuchera* sp. (SIRMa),

267 *Polypodium vulgare* (SIRMm) and *Santolina chamaecyparissus* (SIRMm and SIRMa) showed values that

268 decreased or remained the same during the growing season, hereafter referred to as Category 2. Note

269 that not every species could be sampled at every sampling moment. *Lonicera nitida* has been omitted from

270 this analysis because it was only sampled the first time due to later removal of the walls that contained

271 this species.

14

Temporal variation category 2

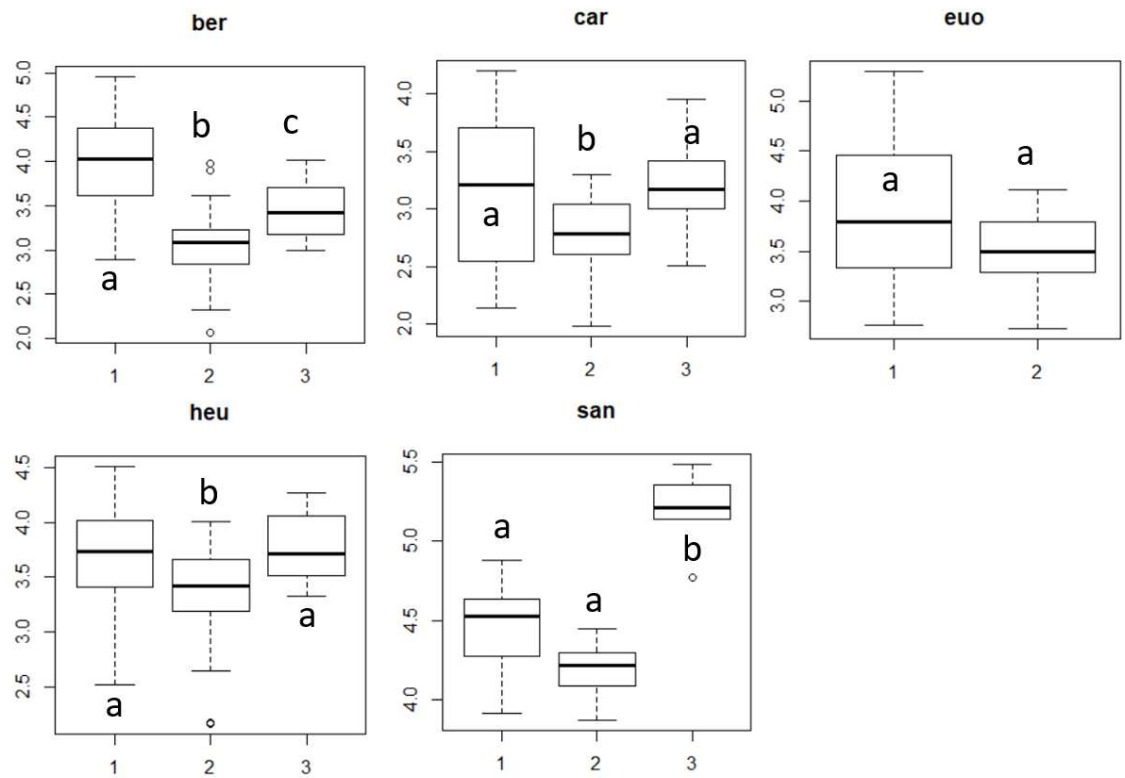$\ln(\text{SIRMm})\ (\mu A.m^2.kg^{-1})$

272

273

15
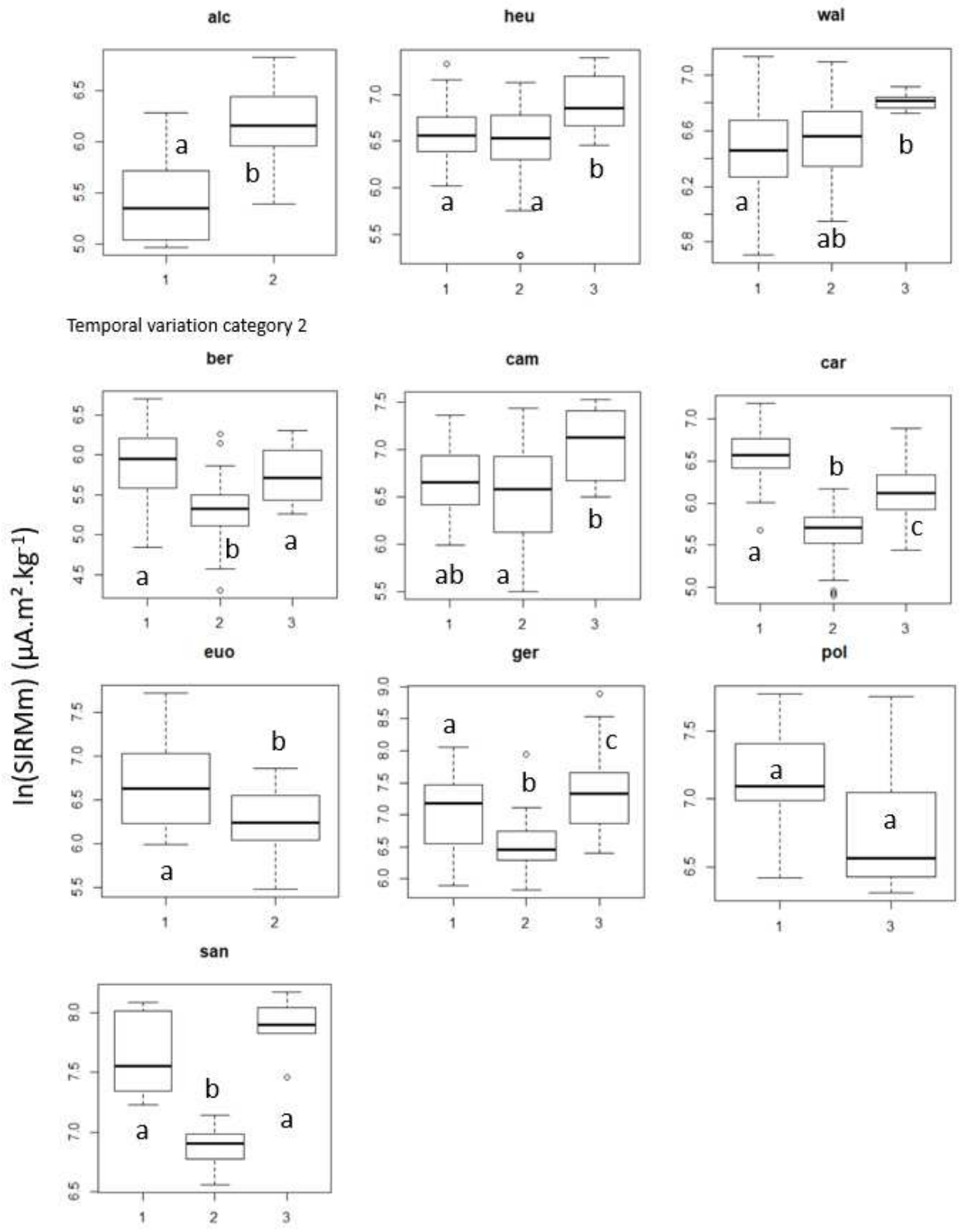
274   Figure 5: Boxplots of temporal variation of the mass normalized SIRM values (SIRMm) for all species

275   (abbreviations are clarified in Appendix table 1) for the three sampling dates: sampling 1 (28-04-2017),

276   sampling 2 (24-08-2017), sampling 3 (20-03-2018). Species with different letters (a-c) are significantly (p <

277   0.05) different.

Temporal variation category 1

Temporal variation category 2

ln(SlRMa) (µA)
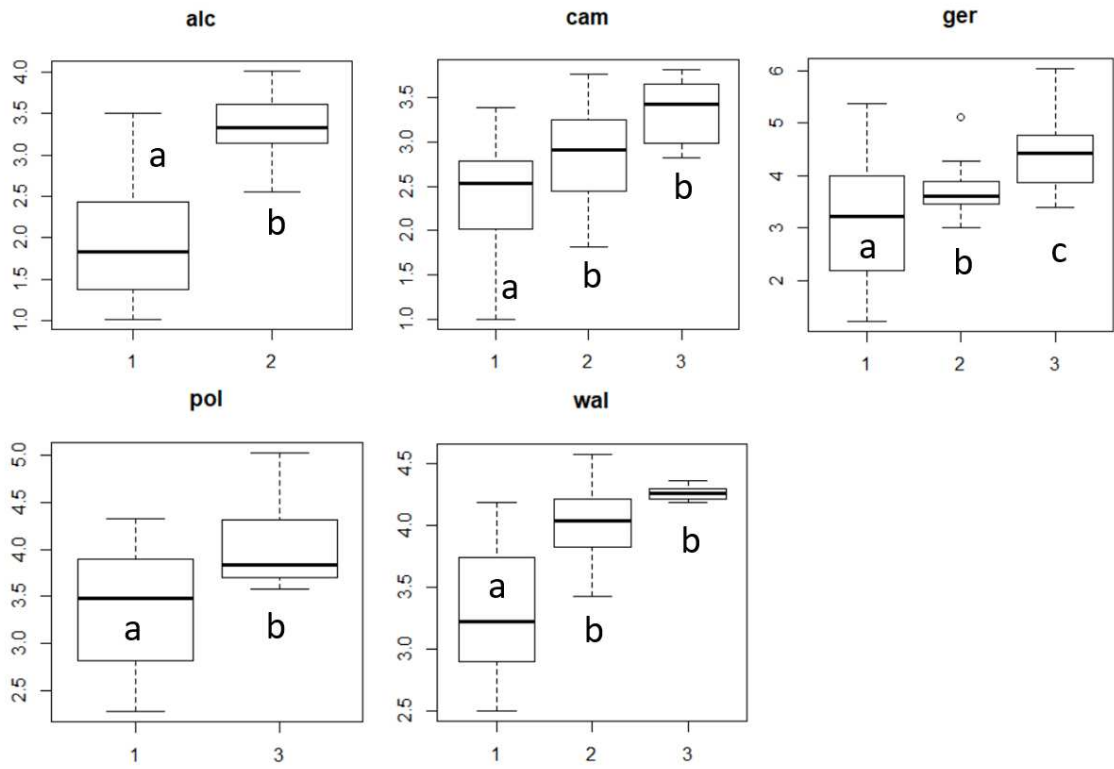
279 Figure 6: Boxplots of temporal variation of the area normalized SIRM values (SIRMa) for all species

280 (abbreviations are clarified in Appendix table 1) for the three sampling dates: sampling 1 (28-04-2017),

281 sampling 2 (24-08-2017), sampling 3 (20-03-2018). Species with different letters (a-c) are significantly (p <

282 0.05) different.

283

284 ## 3.4   Influence of height

285 Vegetation was also sampled at different heights above the ground and this parameter was considered in

286 the same model as the parameters species, sampling time and wall-ID. A indicates the highest sampling

287 point (2.5 ± 0.2 m) on a LWS while C is the lowest (0.5 ± 0.2 m). Significant differences between heights A

288 and B vs. C were found (Fig. 7). For both SIRMm and SIRMa the highest values were found at the lowest

289 sampling height.
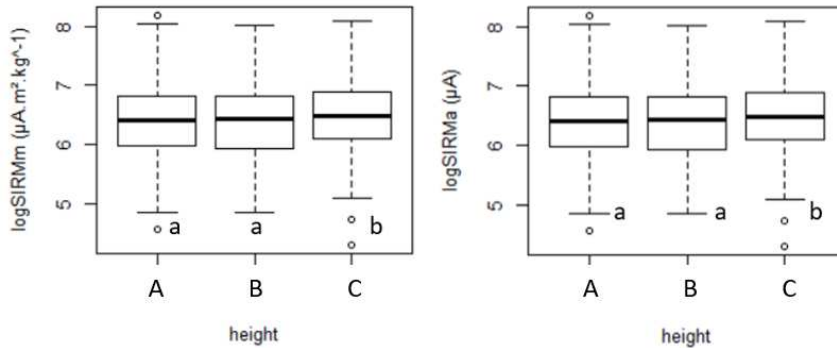
290

291 Figure 7: Boxplots of the three sampling heights (A: 2.5 ± 0.2 m), (B: 1.5 ± 0.2 m) and (C: 0.5 ± 0.2 m).

292 Left: SIRM normalized for mass (SIRMm), right: SIRM normalized for area (SIRMa). Species with different

293 letters (a-b) are significantly (p < 0.05) different.

294

3.5   Effect of morphological parameters

296   All mean values of the morphological parameters are shown in Appendix table 4. Before testing against

297   SIRM values, correlations between all morphological parameters were tested against each other. Only LDI

298   and FLS showed to be negatively correlated (Fig. 8). Furthermore, morphological parameters were

299   statistically tested against mean SIRMm and SIRMa values using a linear model. For SIRMm, no variation

300   could be explained by any of the morphological parameters. However, SIRMa showed almost interaction

301   with SLA in the linear model considering all parameters. Therefore, SLA was isolated and significantly

302   negatively contributed to the variation in SIRMa (p < 0.05, Fig. 8). For *Santolina chamaecyparissus*, no drop

303   contact angle could be determined due to its complex leaf shape.

304
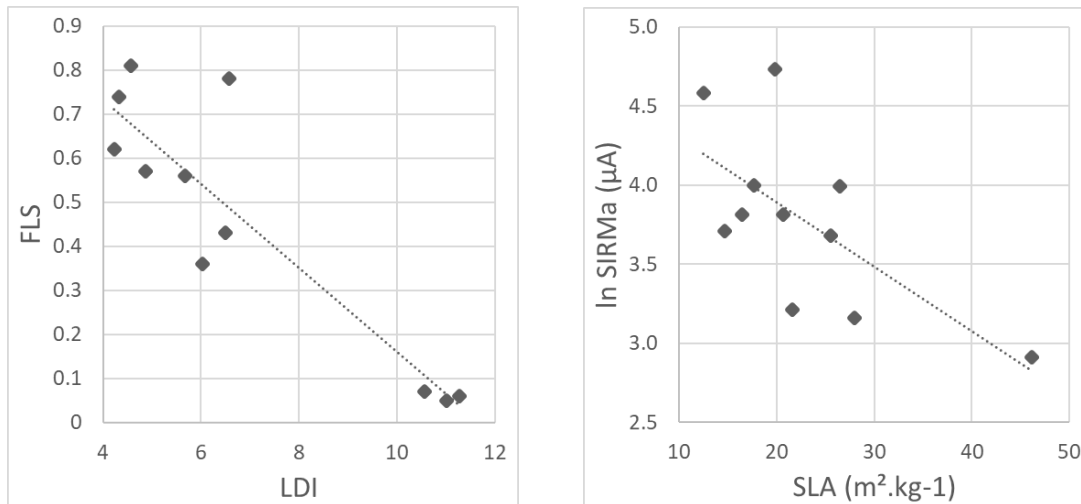
305

306   Figure 8: Left: Correlation between leaf dissection index (LDI) and functional leaf size (FLS). FLS = -

307   0.0953.LDI + 1.1147. R^2 = 0.8137, p < 0.05. Right: Correlation between specific leaf area (SLA, in m².kg^{-1})

308   and the ln of the saturation isothermal remanent magnetization normalized for leaf area (ln SIRMa, in µA).

309   ln SIRMa = -0.0407.SLA + 4.7048. R^2 = 0.4455, p < 0.05.

310

4 Discussion

4.1 Difference in PM accumulation between species

This study is the first to apply the SIRM technique to green wall plant species specifically. Magnetic biomonitoring of plant leaves has been proposed as a good indicator of ambient traffic-derived PM (Castañeda-Miranda et al. 2020; Chen et al. n.d.; Fusaro et al. 2021; Hofman et al. 2013; Matzka and Maher 1999; Winkler et al. 2022). The LWS in this common garden experiment were all exposed to the same source, which allowed the researchers to make use of SIRM as a proxy for leaf deposited PM. When looking at species and their PM load per leaf area (SIRMa) and per mass (SIRMm), large relative differences were found (SIRMa values of 2.74 up to 417 µA). Compared to the range found by Muhammad et al. (2019) (0.7 to 31.6 µA) our SIRMa values are higher. We believe this is partly because of the difference in location of the test site; our common garden had a more open character and was in proximity of a rail road, while the common garden of Muhammad et al. (2019) was in a more secluded area, surrounded by high buildings and trees and further away from a direct pollution source. We must point out that area measurement of *S. chamaecyparissus* may be underestimated, due to the three dimensional shape of the leaves (unlike other species that had more flattened leaves). This could result in an overestimation of SIRMa. However, for SIRMm, *S. chamaecyparissus* also scored highest so it can be assumed that it is generally a good PM accumulator. *L. nitida* and *Geranium* sp. also scored high for both methods. In general, we suspect that relative differences between species are due to differences in morphologies.

4.2 Influence of morphological parameters

In many studies, differences in PM accumulation capacity between species are believed to be caused by the species-specific morphological characteristics (Litschke & Kuttler 2008; Perini et al. 2017; Weerakkody et al. 2017; Muhammad et al. 2019). In this study, seven morphological parameters were assessed

334   (Appendix table 4). A significant negative correlation was found between SIRMa and SLA (Fig. 8, right). This

335   means that leaves with a larger two-dimensional leaf area compared to their dry mass accumulate less PM

336   than e.g. smaller, more rigid leaves. On the left of Figure 8 (right) there are the more 'fleshy' leaves and

337   on the right we see the thinner leaves. This is in accordance with Muhammad et al. (2019, 2020), who

338   suggested that SLA (together with LDI) is a good predictor of PM accumulation and immobilisation by

339   vegetation, as a proxy for the complex interactions of various leaf morphological characteristics. This is

340   valuable for urban managers in terms of optimizing LWS design in terms of urban air quality; smaller, rigid

341   leaves are more desirable.

342   For the other morphological parameters, no correlation with SIRMm or SIRMa values was found. This is in

343   accordance with the findings of Chen et al. (2016), who also found differences in PM capture between

344   species, without demonstrable species-specific criteria. Paull et al. (2019) also found no evidence for the

345   influence of leaf morphology on PM accumulation. It is possible that the total amount of environmental

346   PM was not well enough represented by its magnetic fraction, which usually represents the anthropogenic

347   metallic fraction of PM, in urban contexts often dominated by vehicular traffic (Winkler et al. 2021) in

348   order to determine differences caused by plant morphology. Other literature suggests that grass-like

349   species (like *Carex* sp.) often do not show strong PM accumulation due to their soft or bendable structure

350   that causes less turbulence than over leaves of other vegetation species (Leonard et al. 2016; Weerakkody

351   et al. 2018a). This was also found in our study; *Carex* sp. was situated at the lower end of the net PM

352   accumulation capacity distribution. Moreover, Weerakkody (2018a) found that palmately lobed leaves

353   were the best PM accumulators, regardless of size. In our study however, LDI and FLS, which are measures

354   of leaf shape, had no significant effect on PM capture efficiency. However, they are both correlated with

355   each other (Fig. 8). This is in accordance with Weerakkody et al. (2018a) who also found LDI to be an

356   insignificant parameter. In some literature a rigidity factor is suggested (Koch et al. 2020) and air flow and

357   turbulence may be more important than plant morphology itself (Chen et al. 2016; Koch et al. 2019).

358   Therefore, we suggest wind tunnel experiments where aerodynamic properties (i.e. leaf boundary layer,

359   vegetation porosity, turbulent air flow, etc.) can be monitored and where an aerodynamic indicator can

360   be determined under controlled conditions.

361   Similar to the findings of Perini et al. (2017), Weerakkody et al. (2018b) and Paull et al. (2019), we found

362   no interaction between amount and length of trichomes and PM accumulation. Other researches

363   contradict this (Beckett et al. 2000; Kardel et al. 2012; Saebo et al. 2012; Leonard et al. 2016; Weerakkody

364   et al. 2018a; Muhammad et al. 2019), stating that hairy leaves can capture more PM because the hairs

365   inhibit resuspension by wind or rain, and they increase the surface area available for capture. On the other

366   hand, a high abundance of trichomes makes a leaf hydrophobic, altering leaf wettability, which can result

367   in an opposite effect (Muhammad et al. 2019). We assume this is the case for A. *mollis*. Furthermore, there

368   is also a wide variation of trichome size, length and texture (Weerakkody et al. 2018b) which can result in

369   very different effects. Some of the plant species examined here can be compared with plant species from

370   other manuscripts. In this study *Geranium* sp. has moderate to high PM capture, comparable to *G.*

371   *macrorrhizum* in the study by Weerakkody et al. (2018a). *B. cordifolia* scored low to medium in this study,

372   which was also the case according to Weerakkody et al. (2018a), who attributed this to the smooth surface

373   of the species.

374   Drop contact angle is often seen as a measure for the hydrophobicity or wettability of the epicuticular wax

375   layer, but was in this study also inconclusive with regard to PM accumulation. This is in accordance with

376   the research by Saebo et al. (2012), Kardel et al. (2012) and Leonard et al. (2016). On the other hand,

377   Muhammad et al. (2019) found lower PM accumulation on leaves that were more hydrophobic. We

378   suspect that general microtopography is more important than the presence of hair or wax layer properties

379   such as ridges and grooves. This is also suggested by Kardel et al. (2012).

380

382   The mixed model showed significant differences in PM load on the LWS over the growing season. However,

383   the course between SIRMm and SIRMa is different (Fig. 4), making it necessary to analyze each species

384   separately. The graphs in Figures 10 and 11 show the seasonal variation of individual species. These were

385   divided into two categories. The first category includes all species that have the most obvious result for

386   both PM measuring methods, i.e. an increase over time. This is in accordance to the findings of Wang et

387   al. (2013), among others, who used the gravimetric method for tree species and found that mature leaves

388   had a higher PM load than younger leaves. Our species, evergreen or not, had not changed their leaves

389   yet at the third sampling in the next Spring, which explains the high PM load. *A. mollis* leaves were not yet

390   present at the time of the third sampling as they also emerge later in the season.

391   The second category consists of species whose PM load decreases or remains the same during the growing

392   season and after winter, while new leaves had not yet emerged during the third sampling. For these

393   species, we believe that the decrease or stagnation in PM load during the growing season is mainly due to

394   PM dilution due to rapid leaf expansion. In other words, leaves expand faster than PM is deposited during

395   the growing season (sampling 1 to 2). Because the green walls have controlled watering systems with

396   added nutrients and are therefore in fairly ideal conditions, rapid growth is likely. Hofman et al. (2014)

397   found similar results for *Platanus* leaves when only the leaf encapsulated fraction of PM was considered

398   (when wash-off was excluded), further supporting our hypothesis. Subsequently, when the leaves reach

399   maturation in late summer, PM accumulation per surface or mass will increase again until senescence. An

400   additional explanation for this phenomenon could be the reduction of pollution input at the sampling site

401   during the growing season, similar to the observations by Castanheiro et al. (2020). They observed an

402   increase in PM load during the first six sampling weeks for strawberry, after which PM levels decreased

403   again. Furthermore, resuspension by rainfall or wind can differ greatly between species due to

404   micromorphology and plant porosity (Currie & Bass 2008; Przybysz et al. 2014). In contrast, Ottelé et al.

405 (2010) and Perini et al. (2017) found that seasonal variation did not affect PM accumulation. To further

406 examine seasonal variation and the influence of meteorological conditions, laboratory experiments with

407 controlled precipitation are recommended. It should also be noted that PM assessment techniques differ

408 between our study and some of the literature we refer to (SIRM versus gravimetric or electron microscopic

409 analyses), which makes direct comparison difficult, but general trends should be the same.

410 We believe that the different temporal variation categories are also influenced by leaf age uncertainty; *E.*

411 *fortunei, L. nitida* and *S. chamaecyparissus* are evergreens, while the other species change leaves, but also

412 in different time frames. This makes it very difficult to estimate the actual age of the leaf. In order to

413 counter this, although very labor-intensive, labeling leaves would be a good option.

414

415 4.4 Effect of WLAI

416 Since SIRMa is a PM measure normalized for leaf area, it can be derived from this value how much the PM

417 collection capacity is for a given amount of leaf material. Obviously, WLAI changes throughout the season,

418 but given the large amount of leaves needed and not to visually damage the systems, samples for leaf area

419 determination were only taken during the pruning season. Therefore, each species has only one value for

420 WLAI, which is at least a good representation of the differences between species, and consequently also

421 only one value for totalSIRM. When SIRMa is multiplied with WLAI, the order of species from low to high

422 PM capture capacity changes slightly, but generally remains the same; *S. chamaecyparissus*, *Geranium* sp.

423 and *L. nitida* again perform the best, together with *W. ternata*. In general, a higher WLAI is believed to be

424 better in terms of PM capture (Weerakkody et al. 2017). However, it should be noted that WLAI only

425 expresses the total amount of leaf area per wall area and not the three-dimensional plant configuration.

4.5　Vegetation height

427　In general, biomagnetic monitoring has been proven useful for assessing the three-dimensional spatial

428　distribution of particulates (Mitchell & Maher 2009; Kardel et al. 2011; Hofman et al. 2013). Hofman et al.

429　(2013) found that SIRM values decrease exponentially with tree leaf sampling height and tree crown

430　height, respectively. SIRM is a grainsize dependent magnetic parameter; thus, the use of SIRM as a proxy

431　for the concentration of airborne PM must be done under the assumption that particle size is constant.

432　This could not be the case for different sampling heights, because heavier particles gravitationally stay

433　closer to the ground than finer particles and thus particle size is not equally distributed over the walls

434　vertically. Moreover, the finest ultrafine particles, that are superparamagnetic at room temperature, do

435　not contribute to SIRM. So, for determining the magnetic properties according to the grainsize, the

436　combined used of magnetic susceptibility, hysteresis loops and electron microscopy techniques should be

437　applied.

438　The highest values for both SIRMm and SIRMa were found at the lowest sampling height, i.e. 0.2 – 0.5 m

439　above the ground (Fig. 7). This is in accordance with the majority of literature on the spatial difference in

440　SIRM values. This could mean that, when traffic is the main pollution source, it is most effective when

441　green walls are applied from ground level and upwards for pedestrian health then when they are only

442　applied from a certain building wall height. However, because SIRM is dependent on particle composition

443　and size and heavier particles tend to stay closer to the ground, there is still some uncertainty regarding

444　height differences.

445

446 ## 4.6　Consequences for human health

447　The bioaccumulation of PM in this study was solely defined with SIRM. This technique has proven to be

448　very useful when it comes to biomonitoring analyses and big data collection, in the lab of the researchers

449   and many others (Hofman et al. 2017). However, it has to be noted that this method only works for health

450   assessment when harmful PM is well represented by its magnetic fraction (Winkler et al. 2021).This Is not

451   necessarily the case in this study, as ultrafine particles probably settle at the highest heights, but do not

452   contribute to SIRM, and therefore no suggestions can be given health-wise. In exceptional cases there can

453   even be a negative correlation between SIRM and airborne PM concentrations (Petrovský et al. 2020) .

454   However, because our study was a common garden experiment with the same PM sources and

455   meteorological conditions, we assume this very unlikely. The fact that SIRM does not take into account the

456   smallest magnetic PM fraction (magnetite < 35nm), which also has the most implications for health, also

457   deserves more attention.

458

459   ## 5   Conclusion

460   In this study, 11 commonly used living wall system (LWS) plant species were assessed in a common garden

461   experiment via SIRM (*Saturation isothermal remanent magnetization*, both normalized for leaf area and

462   mass) in terms of relative particulate matter (PM) accumulation and its change over time and in height.

463   Large differences in total SIRM values between species were found. *S. chamaecyparissus*, *Geranium* sp., *L.*

464   *nitida* and *W. ternata* were the best PM capturers. In general, we can conclude that green wall plant

465   species are definitely able to capture PM out of the environment. However, careful species selection and

466   implementation is important. This study shows how complex interactions can be between an engineered

467   vegetation system and its environment and demonstrates the need for optimal plant composition and

468   system design. Specific leaf area (SLA) showed a negative correlation with SIRM normalized for leaf area

469   (SIRMa). This suggests that SLA is a good representative for the leaf morphological complex. Hereby it is

470   interesting for LWS designers, professionally or self-builders, to select plant species based solely on their

471   fleshy or thin appearance, in order to have an idea of their relative PM accumulation capacity, without the

26

472   need for PM analysis on the leaves, which is much more time consuming and expensive. Furthermore,

473   species that perform poorly in PM accumulation per unit area cannot make up for this by simply making

474   lots of leaves. It is important to include wall leaf area index (WLAI) because the species that perform best

475   taking the WLAI into account are not necessarily the species that score highest in terms of PM

476   accumulation (SIRM).

477   For future research we suggest additional laboratory experiments under controlled circumstances: correct

478   leaf age assessment by tagging, leaf expansion, senescence, monitored PM deposition, resuspension and

479   controlled precipitation and irrigation. These 'ideal' conditions could be a proxy for making estimates for

480   outdoor situations, which can then provide a comparison with this experiment. Furthermore it would be

481   useful to asses further magnetic parameters, e.g. sensitive to ultrafine particles or grainsize independent

482   for the total concentration. Taking foliage permeability and porosity into account would also greatly

483   contribute to a better understanding of how air flows through vegetation and its three-dimensional

484   structure. Nevertheless, field experiments examining the systems under their real conditions remain as

485   important.

486

487   6   Acknowledgements

7   Bibliography

EEA. (2017a). *Environmental indicator report 2017: Outdoor air quality in urban areas*. European Environment Agency, Copenhagen.

EEA. (2017b). *Environmental indicator report 2017: Air pollutant emissions.* European Environment Agency, Copenhagen.

Abhijith, K. V., Prashant Kumar, John Gallagher, Aonghus McNabola, Richard Baldauf, Francesco Pilla, Brian Broderick, Silvana Di Sabatino, and Beatrice Pulvirenti. 2017. 'Air Pollution Abatement Performances of Green Infrastructure in Open Road and Built-up Street Canyon Environments – A Review'. *Atmospheric Environment* 162:71–86. doi: 10.1016/j.atmosenv.2017.05.014.

Beckett, K. P., P. H. Freer-Smith, and G. Taylor. 1998. 'Urban Woodlands: Their Role in Reducing the Effects of Particulate Pollution'. *Environmental Pollution* 99(3):347–60. doi: 10.1016/S0269-7491(98)00016-5.

Beckett, K. Paul, P. H. Freer-Smith, and Gail Taylor. 2000. 'Particulate Pollution Capture by Urban Trees: Effect of Species and Windspeed'. *Global Change Biology* 6(8):995–1003. doi: 10.1046/j.1365-2486.2000.00376.x.

Brunekreef, Bert. 1997. 'Air Pollution and Life Expectancy: Is There a Relation?' *Occupational and Environmental Medicine* 54(11):781–84. doi: 10.1136/oem.54.11.781.

Castañeda-Miranda, Ana G., Marcos A.E. Chaparro, Adolfo Pacheco-Castro, Mauro A.E. Chaparro, and Harald N. Böhnel. 2020. 'Magnetic Biomonitoring of Atmospheric Dust Using Tree Leaves of Ficus Benjamina in Querétaro (México)'. *Environmental Monitoring and Assessment* 192(6). doi: 10.1007/s10661-020-8238-x.

514   Castanheiro, Ana, Jelle Hofman, Gert Nuyts, Steven Joosen, Simo Spassov, Ronny Blust, Silvia Lenaerts,

515   Karolien De Wael, and Roeland Samson. 2020. 'Leaf Accumulation of Atmospheric Dust:

516   Biomagnetic, Morphological and Elemental Evaluation Using SEM, ED-XRF and HR-ICP-MS'.

517   *Atmospheric Environment* 221(October 2019):117082. doi: 10.1016/j.atmosenv.2019.117082.

518   Castanheiro, Ana, Roeland Samson, and Karolien De Wael. 2016. 'Magnetic- and Particle-Based

519   Techniques to Investigate Metal Deposition on Urban Green'. *Science of the Total Environment*

520   571:594–602. doi: 10.1016/j.scitotenv.2016.07.026.

521   Chen, Hong, &. Dun-Sheng Xia, Bo Wang, Hui Liu, and Xiaoyi Ma. n.d. 'Pollution Monitoring Using the

522   Leaf-Deposited Particulates and Magnetism of the Leaves of 23 Plant Species in a Semi-Arid City,

523   Northwest China'. doi: 10.1007/s11356-021-16686-1/Published.

524   Chen, Lixin, Chenming Liu, Rui Zou, Mao Yang, and Zhiqiang Zhang. 2016. 'Experimental Examination of

525   Effectiveness of Vegetation as Bio-Filter of Particulate Matters in the Urban Environment'.

526   *Environmental Pollution* 208:198–208. doi: 10.1016/j.envpol.2015.09.006.

527   Currie, Beth Anne, and Brad Bass. 2008. 'Estimates of Air Pollution Mitigation with Green Plants and

528   Green Roofs Using the UFORE Model'. *Urban Ecosystems* 11(4):409–22. doi: 10.1007/s11252-008-

529   0054-y.

530   Declercq, Ynse, Roeland Samson, Ellen Van De Vijver, Johan De Grave, Filip M. G. Tack, and Philippe De

531   Smedt. 2020. 'A Multi-Proxy Magnetic Approach for Monitoring Large-Scale Airborne Pollution

532   Impact'. *Science of the Total Environment* 743:140718. doi: 10.1016/j.scitotenv.2020.140718.

533   Van Dyck, Lieve, Hayat Bentouhami, Kyra Koch, Roeland Samson, and Joost Weyler. 2019. 'Exposure to

534   Indoor Ferromagnetic Particulate Matter Monitored by Strawberry Plants and the Occurrence of

535   Acute Respiratory Events in Adults'. *International Journal of Environmental Research and Public*

536   *Health* 16(23):1–10. doi: 10.3390/ijerph16234823.

537   Dzierzanowski, Kajetan, Robert Popek, Helena Gawrońska, Arne Saebø, and Stanislaw W. Gawroński.

538   2011. 'Deposition of Particulate Matter of Different Size Fractions on Leaf Surfaces and in Waxes of

539   Urban Forest Species'. *International Journal of Phytoremediation* 13(10):1037–46. doi:

540   10.1080/15226514.2011.552929.

541   Freer-Smith, P. H., K. P. Beckett, and Gail Taylor. 2005. 'Deposition Velocities to Sorbus Aria, Acer

542   Campestre, Populus Deltoides x Trichocarpa "Beaupré", Pinus Nigra and x Cupressocyparis Leylandii

543   for Coarse, Fine and Ultra-Fine Particles in the Urban Environment'. *Environmental Pollution*

544   133(1):157–67. doi: 10.1016/j.envpol.2004.03.031.

545   Fusaro, Lina, Elisabetta Salvatori, Aldo Winkler, Maria Agostina Frezzini, Elena De Santis, Leonardo

546   Sagnotti, Silvia Canepari, and Fausto Manes. 2021. 'Urban Trees for Biomonitoring Atmospheric

547   Particulate Matter: An Integrated Approach Combining Plant Functional Traits, Magnetic and

548   Chemical Properties'. *Ecological Indicators* 126. doi: 10.1016/j.ecolind.2021.107707.

549   Gallagher, John, Richard Baldauf, Christina H. Fuller, Prashant Kumar, Laurence W. Gill, and Aonghus

550   McNabola. 2015. 'Passive Methods for Improving Air Quality in the Built Environment: A Review of

551   Porous and Solid Barriers'. *Atmospheric Environment* 120:61–70. doi:

552   10.1016/j.atmosenv.2015.08.075.

553   Hofman, Jelle, Barbara A. Maher, Adrian R. Muxworthy, Karen Wuyts, Ana Castanheiro, and Roeland

554   Samson. 2017. 'Biomagnetic Monitoring of Atmospheric Pollution: A Review of Magnetic Signatures

555   from Biological Sensors'. *Environmental Science and Technology* 51(12):6648–64. doi:

556   10.1021/acs.est.7b00832.

557 Hofman, Jelle, Ines Stokkaer, Lies Snauwaert, and Roeland Samson. 2013. 'Spatial Distribution

558   Assessment of Particulate Matter in an Urban Street Canyon Using Biomagnetic Leaf Monitoring of

559   Tree Crown Deposited Particles.' *Environmental Pollution (Barking, Essex : 1987)* 183:123–32. doi:

560   10.1016/j.envpol.2012.09.015.

561 Hofman, Jelle, Karen Wuyts, Shari Van Wittenberghe, Melanka Brackx, and Roeland Samson. 2014. 'On

562   the Link between Biomagnetic Monitoring and Leaf-Deposited Dust Load of Urban Trees:

563   Relationships and Spatial Variability of Different Particle Size Fractions'. *Environmental Pollution*

564   192:285–94. doi: 10.1016/j.envpol.2014.05.006.

565 Hofman, Jelle, Karen Wuyts, Shari Van Wittenberghe, and Roeland Samson. 2014. 'On the Temporal

566   Variation of Leaf Magnetic Parameters: Seasonal Accumulation of Leaf-Deposited and Leaf-

567   Encapsulated Particles of a Roadside Tree Crown'. *Science of The Total Environment* 493:766–72.

568   doi: 10.1016/j.scitotenv.2014.06.074.

569 Hussain Lakho, Fida, Jarne Vergote, Hafiz Ihsan-ul-haq Khan, Veerle Depuydt, Teun Depreeuw, Stijn Van

570   Hulle, and Diederik Rousseau. 2021. 'Total Value Wall : Full Scale Demonstration of a Green Wall for

571   Grey Water Treatment and Recycling'. *Journal of Environmental Management* 298(July):113489.

572   doi: 10.1016/j.jenvman.2021.113489.

573 Janhäll, Sara. 2015. 'Review on Urban Vegetation and Particle Air Pollution - Deposition and Dispersion'.

574   *Atmospheric Environment* 105:130–37. doi: 10.1016/j.atmosenv.2015.01.052.

575 Jimoda, L. A. 2012. 'Effects of Particulate Matter on Human Health, Climate and Materials: A Review'.

576   *Working and Living Environmental Protection* 9(1):27–44.

577 Kardel, F., K. Wuyts, B. a. Maher, R. Hansard, and R. Samson. 2011. 'Leaf Saturation Isothermal

578   Remanent Magnetization (SIRM) as a Proxy for Particulate Matter Monitoring: Inter-Species

579   Differences and in-Season Variation'. *Atmospheric Environment* 45(29):5164–71. doi:

580   10.1016/j.atmosenv.2011.06.025.

581 Kardel, F., K. Wuyts, B. a. Maher, and R. Samson. 2012. 'Intra-Urban Spatial Variation of Magnetic

582   Particles: Monitoring via Leaf Saturation Isothermal Remanent Magnetisation (SIRM)'. *Atmospheric*

583   *Environment* 55:111–20. doi: 10.1016/j.atmosenv.2012.03.025.

584 Koch, K., R. Samson, and S. Denys. 2019. 'Aerodynamic Characterisation of Green Wall Vegetation Based

585   on Plant Morphology: An Experimental and Computational Fluid Dynamics Approach'. *Biosystems*

586   *Engineering* 178. doi: 10.1016/j.biosystemseng.2018.10.019.

587 Koch, Kyra, Roeland Samson, and Siegfried Denys. 2020. 'Experimental and Computational Aerodynamic

588   Characterisation of Urban Trees'. *Biosystems Engineering* 190(2019):47–57. doi:

589   10.1016/j.biosystemseng.2019.11.020.

590 Koch, Kyra, Tess Ysebaert, Siegfried Denys, and Roeland Samson. 2020. 'Urban Heat Stress Mitigation

591   Potential of Green Walls: A Review'. *Urban Forestry and Urban Greening* 55(July):126843. doi:

592   10.1016/j.ufug.2020.126843.

593 Leonard, Ryan J., Clare McArthur, and Dieter F. Hochuli. 2016. 'Particulate Matter Deposition on

594   Roadside Plants and the Importance of Leaf Trait Combinations'. *Urban Forestry and Urban*

595   *Greening* 20:249–53. doi: 10.1016/j.ufug.2016.09.008.

596 Litschke, Tom, and Wilhelm Kuttler. 2008. 'On the Reduction of Urban Particle Concentration by

597   Vegetation - A Review'. *Meteorologische Zeitschrift* 17(3):229–40. doi: 10.1127/0941-

598   2948/2008/0284.

599   Madre, Frédéric, Philippe Clergeau, Nathalie Machon, and Alan Vergnes. 2015. 'Building Biodiversity:

600   Vegetated Façades as Habitats for Spider and Beetle Assemblages'. *Global Ecology and*

601   *Conservation* 3:222–33. doi: 10.1016/j.gecco.2014.11.016.

602   Maher, Barbara A., Imad A. M. Ahmed, Brian Davison, Vassil Karloukovski, and Robert Clarke. 2013.

603   'Impact of Roadside Tree Lines on Indoor Concentrations of Traffic-Derived Particulate Matter'.

604   *Environmental Science and Technology* 47(23):13737–44. doi: 10.1021/es404363m.

605   Matzka, J., and B. A. Maher. 1999. 'Magnetic Biomonitoring of Roadside Tree Leaves: Identification of

606   Spatial and Temporal Variations in Vehicle-Derived Particulates'. *Atmospheric Environment*

607   33(28):4565–69. doi: 10.1016/S1352-2310(99)00229-0.

608   McLellan, T., and J. A. Endler. 1998. 'The Relative Succes of Some Methods for Measuring and Describing

609   the Shape of Complex Objects'. *Systematic Biology* 47(2):264–81. doi: 10.1080/106351598260914.

610   Mitchell, R., and B. A. Maher. 2009. 'Evaluation and Application of Biomagnetic Monitoring of Traffic-

611   Derived Particulate Pollution'. *Atmospheric Environment* 43(13):2095–2103. doi:

612   10.1016/j.atmosenv.2009.01.042.

613   Muhammad, S., K. Wuyts, and R. Samson. 2019. 'Atmospheric Net Particle Accumulation on 96 Plant

614   Species with Contrasting Morphological and Anatomical Leaf Characteristics in a Common Garden

615   Experiment'. *Atmospheric Environment* 202(January 2019):328–44. doi:

616   10.1016/j.atmosenv.2019.01.015.

617   Muhammad, Samira, Karen Wuyts, Gert Nuyts, Karolien De Wael, and Roeland Samson. 2020.

618   'Characterization of Epicuticular Wax Structures on Leaves of Urban Plant Species and Its

619   Association with Leaf Wettability'. *Urban Forestry and Urban Greening* 47(December 2019):126557.

620   doi: 10.1016/j.ufug.2019.126557.

621   Nowak, David J., Daniel E. Crane, and Jack C. Stevens. 2006. 'Air Pollution Removal by Urban Trees and

622   Shrubs in the United States'. *Urban Forestry and Urban Greening* 4(3–4):115–23. doi:

623   10.1016/j.ufug.2006.01.007.

624   Ottelé, Marc, Hein D. van Bohemen, and a. L. a Fraaij. 2010. 'Quantifying the Deposition of Particulate

625   Matter on Climber Vegetation on Living Walls'. *Ecological Engineering* 36(2):154–62. doi:

626   10.1016/j.ecoleng.2009.02.007.

627   Paull, Naomi J., Daniel Krix, Peter J. Irga, and Fraser R. Torpy. 2019. 'Airborne Particulate Matter

628   Accumulation on Common Green Wall Plants'. *International Journal of Phytoremediation* 0(0):1–13.

629   doi: 10.1080/15226514.2019.1696744.

630   Pérez, Gabriel, Lídia Rincón, Anna Vila, Josep M. González, and Luisa F. Cabeza. 2011. 'Green Vertical

631   Systems for Buildings as Passive Systems for Energy Savings'. *Applied Energy* 88(12):4854–59. doi:

632   10.1016/j.apenergy.2011.06.032.

633   Perini, Katia, Marc Ottelé, Saverio Giulini, Adriano Magliocco, and Enrica Roccotiello. 2017.

634   'Quantification of Fine Dust Deposition on Different Plant Species in a Vertical Greening System'.

635   *Ecological Engineering* 100(January):268–76. doi: 10.1016/j.ecoleng.2016.12.032.

636   Petrovský, Eduard, Aleš Kapička, Hana Grison, Bohumil Kotlík, and Hana Miturová. 2020. 'Negative

637   Correlation between Concentration of Iron Oxides and Particulate Matter in Atmospheric Dust:

638   Case Study at Industrial Site during Smoggy Period'. *Environmental Sciences Europe* 32(1). doi:

639   10.1186/s12302-020-00420-8.

640   Pope III, C. Arden, and Douglas W. Dockery. 2006. 'Health Effects of Fine Particulate Air Pollution: Lines

641   That Connect'. *Journal of the Air and Waste Management Association* 56(6):709–42. doi:

642   10.1080/10473289.2006.10464485.

643   Prodanovic, Veljko, Belinda Hatt, David McCarthy, Kefeng Zhang, and Ana Deletic. 2017. 'Green Walls for

644   Greywater Reuse: Understanding the Role of Media on Pollutant Removal'. *Ecological Engineering*

645   102:625–35. doi: 10.1016/j.ecoleng.2017.02.045.

646   Przybysz, A., A. Sæbø, H. M. Hanslin, and S. W. Gawroński. 2014. 'Accumulation of Particulate Matter and

647   Trace Elements on Vegetation as Affected by Pollution Level, Rainfall and the Passage of Time'.

648   *Science of the Total Environment* 481(1):360–69. doi: 10.1016/j.scitotenv.2014.02.072.

649   Pugh, Thomas a M., a Robert Mackenzie, J. Duncan Whyatt, and C. Nicholas Hewitt. 2012. 'Effectiveness

650   of Green Infrastructure for Improvement of Air Quality in Urban Street Canyons.' *Environmental*

651   *Science & Technology* 46(14):7692–99. doi: 10.1021/es300826w.

652   Rai, Prabhat Kumar. 2016. 'Impacts of Particulate Matter Pollution on Plants: Implications for

653   Environmental Biomonitoring'. *Ecotoxicology and Environmental Safety* 129:120–36. doi:

654   10.1016/j.ecoenv.2016.03.012.

655   Sæbø, A., R. Popek, B. Nawrot, H. M. Hanslin, H. Gawronska, and S. W. Gawronski. 2012. 'Plant Species

656   Differences in Particulate Matter Accumulation on Leaf Surfaces'. *Science of the Total Environment*

657   427–428:347–54. doi: 10.1016/j.scitotenv.2012.03.084.

658   Shao, Yiming, Jiaqiang Li, Zhiwei Zhou, Fan Zhang, and Yuanlong Cui. 2021. 'The Impact of Indoor Living

659   Wall System on Air Quality: A Comparative Monitoring Test in Building Corridors'. *Sustainability*

660   *(Switzerland)* 13(14). doi: 10.3390/su13147884.

661   Solomon, Paul A., Maria Costantini, Thomas J. Grahame, Miriam E. Gerlofs-Nijland, Flemming R. Cassee,

662   Armistead G. Russell, Jeffrey R. Brook, Philip K. Hopke, George Hidy, Robert F. Phalen, Paulo Saldiva,

663   Stefanie Ebelt Sarnat, John R. Balmes, Ira B. Tager, Halûk Özkaynak, Sverre Vedal, Susan S. G.

664   Wierman, and Daniel L. Costa. 2012. *Air Pollution and Health: Bridging the Gap from Sources to*

665   *Health Outcomes: Conference Summary*. Vol. 5.

666 Stalder, Aurélien F., Tobias Melchior, Michael Müller, Daniel Sage, Thierry Blu, and Michael Unser. 2010.

667   'Low-Bond Axisymmetric Drop Shape Analysis for Surface Tension and Contact Angle

668   Measurements of Sessile Drops'. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*

669   364(1–3):72–81. doi: 10.1016/j.colsurfa.2010.04.040.

670 Sternberg, Troy, Heather Viles, Alan Cathersides, and Mona Edwards. 2010. 'Dust Particulate Absorption

671   by Ivy (Hedera Helix L) on Historic Walls in Urban Environments'. *Science of the Total Environment*

672   409(1):162–68. doi: 10.1016/j.scitotenv.2010.09.022.

673 Tallis, Matthew J., Jorge Humberto Amorim, Carlo Calfapietra, Peter Freer-Smith, Sue Grimmond, and

674   Simone Kotthaus. 2015. 'The Impacts of Green Infrastructure on Air Quality and Temperature'.

675   *Handbook on Green Infrastructure* (November):30–49. doi: 10.4337/9781783474004.00008.

676 Viecco, Margareth, Sergio Vera, Héctor Jorquera, Waldo Bustamante, Jorge Gironás, Cynnamon Dobbs,

677   and Eduardo Leiva. 2018. 'Potential of Particle Matter Dry Deposition on Green Roofs and Living

678   Walls Vegetation for Mitigating Urban Atmospheric Pollution in Semiarid Climates'. *Sustainability*

679   *(Switzerland)* 10(7). doi: 10.3390/su10072431.

680 Vos, Peter E. J., Bino Maiheu, Jean Vankerkom, and Stijn Janssen. 2012. 'Improving Local Air Quality in

681   Cities: To Tree or Not to Tree?' *Environmental Pollution* 183:113–22. doi:

682   10.1016/j.envpol.2012.10.021.

683 Wang, Huixia, Hui Shi, Yangyang Li, Ya Yu, and Jun Zhang. 2013. 'Seasonal Variations in Leaf Capturing of

684   Particulate Matter, Surface Wettability and Micromorphology in Urban Tree Species'. *Frontiers of*

685   *Environmental Science and Engineering* 7(4):579–88. doi: 10.1007/s11783-013-0524-1.

686   Weber, Frauke, Ingo Kowarik, and Ina Säumel. 2014. 'Herbaceous Plants as Filters: Immobilization of

687   Particulates along Urban Street Corridors'. *Environmental Pollution* 186:234–40. doi:

688   10.1016/j.envpol.2013.12.011.

689   Weerakkody, Udeshika, John W. Dover, Paul Mitchell, and Kevin Reiling. 2017. 'Particulate Matter

690   Pollution Capture by Leaves of Seventeen Living Wall Species with Special Reference to Rail-Traffic

691   at a Metropolitan Station'. *Urban Forestry and Urban Greening* 27(July):173–86. doi:

692   10.1016/j.ufug.2017.07.005.

693   Weerakkody, Udeshika, John W. Dover, Paul Mitchell, and Kevin Reiling. 2018a. 'Evaluating the Impact of

694   Individual Leaf Traits on Atmospheric Particulate Matter Accumulation Using Natural and Synthetic

695   Leaves'. *Urban Forestry & Urban Greening* 30(January):98–107. doi: 10.1016/j.ufug.2018.01.001.

696   Weerakkody, Udeshika, John W. Dover, Paul Mitchell, and Kevin Reiling. 2018b. 'Quantification of the

697   Traffic-Generated Particulate Matter Capture by Plant Species in a Living Wall and Evaluation of the

698   Important Leaf Characteristics'. *Science of the Total Environment* 635:1012–24. doi:

699   10.1016/j.scitotenv.2018.04.106.

700   Weerakkody, Udeshika, John W Dover, Paul Mitchell, and Kevin Reiling. 2018. 'The Impact of Rainfall in

701   Remobilising Particulate Matter Accumulated on Leaves of Four Evergreen Species Grown on a

702   Green Screen and a Living Wall'. *Urban Forestry & Urban Greening* 35:21–31. doi:

703   10.1016/j.ufug.2018.07.018.

704   White, Emma V., and Birgitta Gatersleben. 2011. 'Greenery on Residential Buildings: Does It Affect

705   Preferences and Perceptions of Beauty?' *Journal of Environmental Psychology* 31(1):89–98. doi:

706   10.1016/j.jenvp.2010.11.002.

707   Winkler, Aldo, Antonio Amoroso, Alessandro Di Giosa, and Giada Marchegiani. 2021. 'The Effect of Covid-

708   19 Lockdown on Airborne Particulate Matter in Rome, Italy: A Magnetic Point of View'.

709   *Environmental Pollution* 291. doi: 10.1016/j.envpol.2021.118191.

710   Winkler, Aldo, Tania Contardo, Virginia Lapenta, Antonio Sgamellotti, and Stefano Loppi. 2022. 'Assessing

711   the Impact of Vehicular Particulate Matter on Cultural Heritage by Magnetic Biomonitoring at Villa

712   Farnesina in Rome, Italy'. *Science of the Total Environment* 823. doi:

713   10.1016/j.scitotenv.2022.153729.

714   Wong, Nyuk Hien, Alex Yong Kwang Tan, Yu Chen, Kannagi Sekar, Puay Yok Tan, Derek Chan, Kelly

715   Chiang, and Ngian Chung Wong. 2010. 'Thermal Evaluation of Vertical Greenery Systems for

716   Building Walls'. *Building and Environment* 45(3):663–72. doi: 10.1016/j.buildenv.2009.08.005.

717   van de Wouw, P. M. F., E. J. M. Ros, and H. J. H. Brouwers. 2017. 'Precipitation Collection and

718   Evapo(Transpi)Ration of Living Wall Systems: A Comparative Study between a Panel System and a

719   Planter Box System'. *Building and Environment* 126(July):221–37. doi:

720   10.1016/j.buildenv.2017.10.002.

721   Ysebaert, Tess, Kyra Koch, Roeland Samson, and Siegfried Denys. 2021. 'Green Walls for Mitigating Urban

722   Particulate Matter Pollution—A Review'. *Urban Forestry and Urban Greening* 59(November

723   2020):127014. doi: 10.1016/j.ufug.2021.127014.

724

The influence of plant species, leaf morphology, height and season on PM capture efficiency in living wall systems
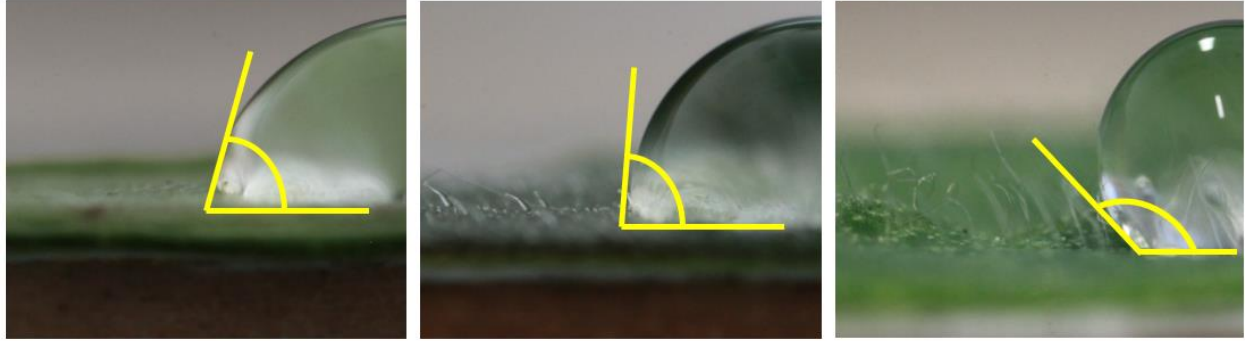
Appendix

Figures

Appendix Figure 1: Location of the Testing Center for Floriculture (Proefcentum voor Sierteelt) in proximity of Ghent city and the Port of Ghent (Gent Zeehaven) in the North. Inset: Red arrow indicates the nearest road; blue arrow indicates the rail road. (Source: Google Maps)

Appendix Figure 2: Several individual test walls on the facility at PCS, Destelbergen. Wall X was placed later, and therefore not tested.
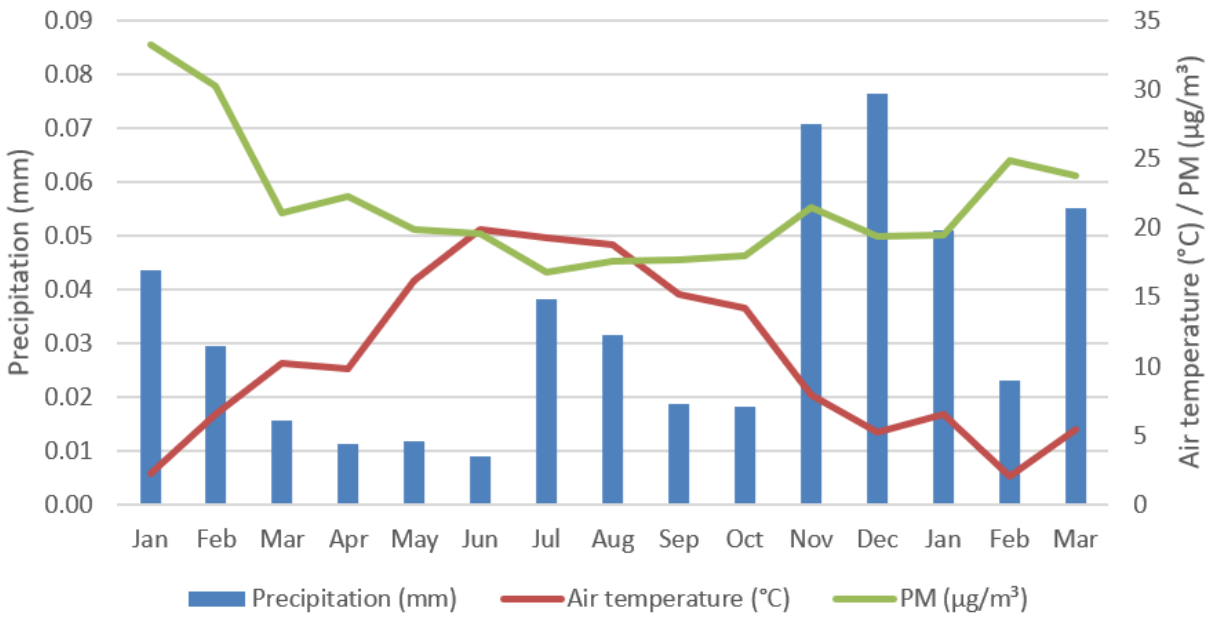
Appendix Figure 3: Average monthly air temperature (red line), average monthly PM concentration (green line) and monthly precipitation (blue bars) from 1/01/2017 until 20/03/2018 (station M701, Tolhuiskaai, Gent and station 44R710) (source: Flanders Environmental Agency (VMM)).

Appendix Figure 4: drop contact angle: different angles are shown in the pictures. Hairiness: from left to right; no visible hairs (class 0), short or few visible hairs (class 1) and many or long visible hairs (class 2) as viewed through the macro lens.

Tables

Table 1: Overview of all investigated plant species, their leaf shape and the abbreviations used in the text are mentioned between brackets. Photos are not actual size, nor relative size to each other.

Alchemilla mollis (alc)	Bergenia cordifolia (ber)	Campanula sp. (cam)	Carex sp. (car)
Euonymus fortunei (euo)	Geranium sp. (ger)	Heuchera sp. (heu)	Lonicera nitida (lon)
Polypodium vulgare (pol)	Santolina chamaecyparissus (san)	Waldsteinia ternata (wal)	

Table 2: Plant species that were sampled on the different living wall systems throughout the experiment. Numbers indicate wall-ID. Species that were sampled at all three sampling dates at a certain wall are indicated with a '*'.

Species	28 April 2017	24 August 2017	20 March 2018
A. mollis	8	8, 11, 13	
B. cordifolia	1, 2, 3, 4, 6*, 8*, 11, 13	4, 6*, 8*, 11, 13	6*, 8*, 13
Campanula sp.	2, 5, 6*, 12,	5, 6*, 12	6*
Carex sp.	7*, 9*, 12, 13*	7*, 8, 9*, 12, 13*	7*, 8, 9*, 13*
E. fortunei	2, 3, 4, 5	5	
Geranium sp.	1, 7*, 8*, 12, 13	7*, 8*, 12, 13,	7*, 8*
Heuchera sp.	3, 4, 6, 9, 11, 12	4, 6, 9, 11, 12	6, 9
L. nitida	1, 11		
P. vulgare	6, 9		6
S. chamaecyparissus	7*	7*	7*
W. ternate	2, 3, 4, 5, 6 *	4, 5, 6*	6*

Table 3: Average wind directions per month prior to and during the sampling period. N = north, E = east, S = south, W = west (station 44R701, Baudelohof, Gent (source: Flanders Environmental Agency (VMM)).

	2017												2018		
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Wind direction	S	S	S	WSW	S	S	SW	SSW	SSW	SW	WSW	SW	SSW	SE	S

Table 4: Average morphological leaf variables +/- standard deviation for all species. DCA = drop contact angle (ad = adaxial, ab = abaxial)(degrees), SLA = specific leaf area ($m^2 \cdot kg^{-1}$), LDI = leaf dissection index (dimensionless), FLS = functional leaf size (dimensionless), hairiness categories: no visible hairs (0), short hairs (1) and long hairs (2). NA = not applicable.

Species	WLAI	DCA (ad)	DCA (ab)	SLA	LDI	FLS	Hairiness
A. mollis	2.37	149 (± 0.12)	146 (± 1.16)	21.63 (± 6.58)	5.68 (± 0.33)	0.56 (± 0.11)	2
B. cordifolia	2.32	96 (±1.21)	56 (± 0.75)	14.70 (± 6.44)	4.32 (± 0.12)	0.74 (± 0.06)	0
Campanula sp.	5.41	77 (± 0.59)	76 (± 1.90)	46.11 (± 11.90)	4.87 (± 0.20)	0.57 (± 0.06)	1
Carex sp.	1.61	70 (± 3.06)	107 (± 1.52)	27.96 (± 4.43)	10.56 (± 0.92)	0.07 (± 0.01)	1
E. fortunei	2.66	76 (± 0.64)	92 (± 0.42)	17.71 (± 0.71)	4.57 (± 0.28)	0.81 (± 0.05)	0
Geranium sp.	8.19	93 (±1.10)	105 (± 0.80)	26.50 (± 6.41)	6.04 (± 1.04)	0.36 (± 0.17)	2
Heuchera sp.	6.60	98 (± 0.94)	120 (± 0.74)	25.51 (± 5.04)	6.50 (± 0.51)	0.43 (± 0.09)	2
L. nitida	28.94	103 (± 1.52)	86 (± 1.40)	12.49 (± 0.43)	4.23 (± 0.33)	0.62 (± 0.05)	0
P. vulgare	2.61	98 (± 1.34)	99 (± 1.15)	16.49 (± 4.78)	11.02 (± 4.03)	0.05 (± 0.03)	0
S. chamaecyparissus	24.04	NA	NA	19.79 (± 2.78)	11.28 (± 2.09)	0.06 (± 0.03)	2
W. ternata	41.54	112 (± 2.51)	92 (± 0.88)	20.66 (± 6.20)	6.57 (± 0.39)	0.78 (± 0.08)	2