# The role of shrubs and perennials in the capture and mitigation of particulate air pollution in London.

**Kyle Shackleton*,Nigel Bell, Hannah Smith, Linda Davies.**

**Centre for Environmental Policy, Imperial College London**
*** kyle.shackleton10@gmail.com**

**(*Convolvulus cneorum* photographed at Swiss Cottage by Kyle Shackleton).**

Imperial College London

# The role of shrubs and perennials in the capture and mitigation of particulate air pollution in London.

**Kyle Shackleton, Hannah Smith, Linda Davies, Nigel Bell.**

## Abstract

Particulate air pollution ($PM_{10}$) is a major health issue in cities of both the developed and developing world, with London having a particularly severe problem in the former case where air pollution is predicted to cause over 4000 premature deaths annually. Currently $PM_{10}$ levels in many parts of London still exceed the EU Limit values, despite attempts to reduce these.This non-compliance presents the UK with the risk of being fined £300 million per annum. Motor vehicle exhaust emissions are responsible for a substantial proportion of urban particulates and their reduction presents the largest challenge to improving the air quality of London and meeting the Directive requirements. The 2010 Mayor of London's Air Quality Report has suggested that an increased level of urban greening has the potential to achieve local reductions in particulates and recently a major programme has been initiated in which a range of plant species in the form of green walls and towers are being installed at selected sites in central London.

The present paper uses a leaf washing and filtration methodology to measure the mass of $PM_{2.5\text{-}10}$ captured per unit surface area of different species, and thus investigates the efficiency of different species and the leaf surface characteristics involved in aiding particulate capture.We also performed calculations on the total PM capture capable by a green wall in our study (Edgware Road). The present study indicated that plants with small leaves with a high density of hairs were most efficient at intercepting $PM_{2.5\text{-}10}$, but during sustained periods of dry weather plants may reach a saturation point, after which particulate capture is less efficient. Conclusions are that urban greening strategies designed to reduce particulates can be used as a supplementary approach to emissions reductions policies, but should be viewed in the context of their wider benefits.

# Table of Contents

## Introduction

Urbanisation by its very nature creates a vast amount of pollution. Particulate emissions in the air constitute a significant portion of this pollution and can have adverse effects on human health. The primary source of particulate emissions in London is road vehicles (GLA 2010). Particulate air pollution can be defined as an air-suspended mixture of both solid and liquid particles (Dockery & Pope 1994). The fraction of concern of these particles, having a diameter < 10 µm, is termed $PM_{10}$. The coarse fraction of $PM_{10}$ on which this study concentrates, ranges from 2.5-10 µm. Size is an important factor in classifying particulates, because size determines the end point of the particle when breathed into the human respiratory system. This can cause a multitude of health problems for humans when the particles penetrate into the bronchi and lungs including cardiovascular disease (Zanobetti*et al*. 2003) and particulate emissions are thought to be responsible for over 4000 premature deaths annually in London alone. This problem will only become worse as urbanisation continues with a greater proportion of the population moving to live in urban areas and the increase in vehicle use associated with this increase in population.

The WHO 2005 air quality guidelines state that PM10 concentrations must not exceed an annual mean of 20µg/m3 or exceed a 24 hours mean of 50µg/m3 (WHO, 2006). However, the guidelines provided some flexibility in the form of three interim targets. Rapid improvements in particulate air quality did not appear to be realistic and therefore a gradual approach was put in place to promote a shift to lower concentrations (Krzyzanowski& Cohen, 2008). The interim targets were aimed mainly at developing countries that are still rapidly industrialising and as a result, have higher particulate concentrations.

In the past 30 years, there has been a significant level of growth in road traffic activity in Europe (Williams, 2000). The increased use of automobiles has partially contributed to the difficulties EU countries have faced in regards to abiding by the limits set in the first Daughter Directive (99/30/EC), which was part of the Air Quality Framework Directive (96/62/EC). This stated that by the 1st of January 2005 the daily mean $PM_{10}$ concentration cannot exceed 50µg/m-3 more than 35 times per year and the annual mean concentration cannot exceed 40µg/m-3.

Between 2005 and 2007, twenty member states requested time extensions under article 22 of Directive 2008/50/EC. The reason for these requests was due to certain zones within the countries failing to meet the standards set. Extensions were granted to the zones where all appropriate measures had been taken on the national, regional and local scales and that the Limit Value was impossible to achieve due to "*site- specific dispersion characteristics, adverse climatic conditions or transboundary contributions*" (Directive 2008/50/EC, 2008). The 2008 Directive stated that accepted zones were exempt from the values set by the first Daughter Directive for three years, ending in June 2011.

Since the first Daughter Directive entered into force in 2005, London has breached the EU limits every year. The UK could now be fined £300 million per annum for this breach.

The 2002 'Mayor's Air Quality Strategy Report' highlighted the main aims and objectives to ensure the 2005 EU limit values for $PM_{10}$, amongst other pollutants, will be met (GLA, 2002). The primary focus of the report was to enforce mechanisms which will reduce the amount of pollution derived from road transport. A dual approach was implemented to attempt to reduce both the overall number of vehicles on the road and the emissions released per vehicle. The main methods for achieving these objectives in London were via the congestion charge, low emission zones and adoption of cleaner vehicles. The 2010 mayor's air quality strategy emphasised further improvements and expansions to the schemes that are already in place.

Although the numerous interventions implemented in central London can account for some reductions in $PM_{10}$ concentrations, it has not been significant enough to ensure London meets the EU limit values. Improvements have been made across London as the average concentration has remained under the EU limit value since 2005 in all categories. However, individual sites continue to exceed the limit and therefore result in the whole of London breaching the EU directive.

The 2010 Mayor's Air Quality Report acknowledges this issue and highlights the need for more local measures. One of the key future objectives is to increase the level of urban greening. It has been suggested that this can act as a possible mitigating method to help reduce the concentration of $PM_{10}$ on a more local scale.

Trees have been found to possess the optimum characteristics when compared to other vegetation forms. Due to their large collecting surface area, increased roughness and the promotion of vertical transport which enhances turbulence, trees are more efficient than shorter vegetation (McDonald et al., 2007). As a consequence, there is a substantial amount of research available which focuses on the benefits of trees as particulate sinks, particularly the differences between broad-leaved and conifer species (Freer-Smith *et al.* 2005). However, other forms of vegetation such as shrubs and more complex biogenic regulators such as green walls have been relatively overlooked.

Whereas previous research on urban greening as a tool to capture particulates has focused primarily on tree species, we seek to expand upon this by examining the role smaller plants can play. Shrubs and perennials, while not as large as trees, present several advantages over trees as tools to mitigate particulate emissions including monetary cost, logistics of planting, and a greater variety of species from which to choose. This study aims to expand on this previous research (Smith 2011), by quantifying the $PM_{2.5-10}$ capture of a range of shrub species. Based on a pilot study from the previous year, we will look at the efficiency and efficacy of different species and quantify the characteristics which allow certain species to outperform others including:

- Leaf hair density.
- Leaf size.
- How particulates accumulate over time.
- The orientation of the plant relative to the pollution source.
- Take into account local, ambient, modelled $PM_{10}$ concentrations.

## Methods.

*Site descriptions*

Four sites in Londondesignated as priority areas for $PM_{10}$ reduction by TFL, were selected to sample vegetation for the capture of $PM_{10}$ (table 1). Each site had received additional greening as a result of the Clean Air Fund (CAF) and was located near a pollution monitoring station.

**Table 1: Location and description of each site.**

| Site | Description | Genera | Annual mean modelled $PM_{10}$ ($\mu g.m^{-3}$) * |
|---|---|---|---|
| Edgware Road | Living wall | *Acorus, Carex, Erysimum, Euonymus, Geranium, Heuchera, Lavendula, Stachys.* | 30 |
| Swiss Cottage | Shrub beds | *Aucuba, Convolvulus, Prunus.* | 31 |
| Lower Thames Street | Planted towers | *Geranium, Hedera* | 32 |
| Park Lane | Shrub beds | *Berberis, Hebe (×2), Viburnum* | 37 |

* (Data from static.london.gov.uk)

Plant species at each site were selected on the basis of the quality and quantity of their foliage upon first visit to the site. Species which were too small were discounted from the study, as removing a large enough sample to be meaningful may have damaged the plant in the long term. Ten samples of each plant species were taken each month for four months between December – March 2012. Each species was assigned a category based on its leaf surface characteristics (table 2).Further information on each species including their leaf surface characteristics can be found in table 3.

**Table 2: Leaf surface classification.**

| Leaf traits | Rank assigned |
|---|---|
| Glabrous (= hairless) | 1 |
| Rough, or hairs present at density of < 100 $cm^{-2}$ | 2 |
| Hairs present at > 100 $cm^{-2}$ | 3 |

Secondly, we investigated the role that a plant's orientation can have on its particulate capture. $PM_{10}$ capture was compared on 41 *Hedera helix* towers of Lower Thames Street between the side facing the road and the side facing the pavement.

**Table 3: Species descriptions (MLSA = mean leaf surface area in $cm^2$, HD = Hair density).**

| | |
|---|---|
| *Acorusgramineus* – Dwarf sedge<br>A small, shrubby monocot native to eastern Asia. Leaves ensiform, approx. 1 cm wide and 6-10 cm long with a smooth, glossy, glabrous surface. MLSA = 6.8, HD = 1. |  |
| *Aucuba japonica* – spotted laurel<br>A potentially large shrub (up to 5m) native to eastern Asia. Leaves 5 – 10 centimetres long and 2 – 5 cm wide with a broad, lanceolate shape, serrate margins and a glabrous and glossy surface. Bears small flowers and red berries in April – May. MLSA = 29.8, HD = 1. |  |

| | |
|---|---|
| *Carextestacea* – Orange New Zealand sedge<br>A shrubby sedge (monocot) native to New Zealand. Leaves ensiform approx. 0.4 cm wide and 10 - 15 cm long with a rough, glabrous surface. MLSA = 4.8, HD = 2. |  |
| *Convolvulus cneorum* – Silverbush<br>A shrub native to southern Europe. Leaves are small and elliptical approx. 0.7 cm wide and 2-3 cm long. Leaf surface is covered in a high density of fine silver hairs. Flowers in spring are white and attractive to pollinators. MLSA = 1.9, HD = 3. |  |
| *Erysimumbicolor*<br>A small, short-lived perennial brassica native to Europe. Leaves are oblong approx. 0.6 cm wide and 5-6 cm long grouped in a rosette. Flowers in late spring with bright pink colouration and are attractive to pollinators. Leaf surface with a high density of short hairs. MLSA = 3.4, HD = 3. |  |

| | |
|---|---|
| *Euonymus fortunei* – Emerald ‘n’ Gold winter creeper<br>A small shrub native to eastern Asia. Leaves are broad, ovate approx. 2 cm long and 1 - 1.5 cm wide with a smooth, glabrous surface. MLSA = 2.4, HD = 1. |  |
| *Geranium maculatum* – Wild geranium.<br>A shrub native to eastern North America. Leaves are broad and palmate approx. 5-7 cm wide and long with 5 or 7 lobes and serrate leaf margins. Surface with fine hairs particularly at the margin of the leaf. Flowers early summer and attracts insects. MLSA = 16.6, HD = 2. |  |
| *Hebe odora*<br>A small shrub native to New Zealand. *Hebe spp.* are characterised by having four rows of perpendicular leaves running up the stem. Leaves in *H. odora* are very small, approx. 0.5 cm wide and 1-1.5 cm long and elliptical in shape. The leaf surface is glabrous. Flowers early summer. MLSA = 0.7, HD = 1 |  |

| | |
|---|---|
| *Hebe* 'Mrs Winder'<br>Another variety of *Hebe* native to New Zealand. *Hebe* 'Mrs Winder' is larger than *H. odora* with larger leaves, approx. 0.7 cm wide and 3 cm long with a purple colouration and glabrous surface. Flowers early summer. MLSA = 2.2, HD = 1 |  |
| *Hedera helix* – English ivy<br>A climbing plant native to Britain and the rest of Europe, potentially growing to 30 m. Leavess may either be palmate with 3 or 5 lobes or cordate, approx. 5-10 cm long and wide with a smooth glossy, glabrous surface. Flowers late summer providing a nectar source for insects and berries which can be forage for birds. MLSA = 21.9, HD = 1. |  |
| *Heucheravillosa* – Hairy alumroot<br>A small perennial native to the eastern United States. Leaves are purple, large and broad with serrate margins. Approx. 5-8 cm long and wide, with hairs at a low density on the leaf surface but higher on the underside of the midrib and stem. MLSA = 21.0, HD = 2. |  |

| | |
|---|---|
| *Lavendulaangustifolia*– Common lavender<br>An aromatic shrub native to the Mediterranean region. Leaves are small approx. 0.5 cm wide and 2-4 cm long with a somewhat rough surface. Flowers in mid-summer, very fragrant and attractive to many pollinators. MLSA = 1.7, HD = 2. |  |
| *Stachys byzantina* – Lamb's ear<br>A perennial herb native to the Middle East. Medium sized leaves are very distinctive due to the long, dense, silver, silky-lanate hairs on the surface. Leaves are elliptical in shape approx. 2 cm wide and 4-5 cm long. Flowers early summer. MLSA = 8.9, HD = 3. |  |
| *Viburnum tinus*<br>A shrub with medium sized elliptical leaves rounded at the base. Approx. 2 cm wide and 4-6 cm long with a smooth, glossy, glabrous surface. White flowers in spring attractive to pollinators. MLSA = 6.0, HD = 1. |  |

| | |
|---|---|
| *Berberisjulianae* – Wintergreen barberry. Large woody shrub. Leaves are lanceolate approx. 1.5 – 2 cm wide and 5 – 10 cm long with glabrous surface and spines protruding from the margin. Flowers in spring and bears pruple berries shortly thereafter. MLSA = 11.0, HD = 1. |  |
| *Prunuslaurocerasus* – Cherry Laurel A shrub with medium sized elliptical leaves approx. 2 – 2.5 cm wide and 6 – 8 cm long with a smooth, glossy, glabrous surface. MLSA = 10.0, HD = 1. |  |

One further species, *Cotoneaster integrifolius* (entire-leaved cotoneaster) planted at the Swiss Cottage site, was due to be a part of this study. Unfortunately, it failed to establish well after planting which resulted in large patches of bare earth. This highlights the importance of selecting and maintaining plants hardy enough to withstand the urban environment.

*Leaf sampling*

Plants from each species on each site were assigned a number, and selected for sampling through a random number generator. Sampling was performed with replacement on different site visits (the same plant could be sampled in January and February) but without replacement within a single visit (the same plant could not be sampled twice in January). Sampling was performed at a uniform height of between 1.5 m where possible, all plants were of a similar distance to the nearest PM source (road) and samples were taken from the side of the plant facing the PM source except in the orientation study. In the second part of the study concerning the effect of orientation on PM capture, all ivy plants at the sitenot on the central reservation were sampled once on each side (n = 41).

We aimed to remove approximately 0.1 $m^2$ of vegetation from each individual plant where possible, however, being young and newly planted there was often less than this amount of vegetation on the whole plant. This was a particular issue on the Edgware Road green wall where in some cases less than 0.01 $m^2$ of vegetation was removed.

Leaves were removed by hand at the petiole, taking care not to touch the leaf surface and remove any particulates prior to washing.

### *Filtration*

Filter papers were pre-dried in an80°C oven for 60 minutes and pre-weighed on a microbalance (Dzierżanowskia*et al.* 2011). Papers were allowed to equilibrate to weighing room conditions for 1 hour prior to weighing. Particulate matter was washed from each leaf sample by agitating in a polythene bag with 100 ml of distilled water for 3 minutes (Lovett & Lindberg 1992). The leaves were then scrubbed with a 2.5cm clean no hair loss paintbrush to ensure all the particles were washed off into the solution (Beckett *et al.* 2000). The solution was filtered through cellulose nitrate filter paper with a pore size of 10µm to remove the fraction of particulates larger than $PM_{10}$,then through cellulose nitrate filter paper with a pore size of <2.5µm to collect the $PM_{2.5-10}$ fraction.Filter papers were dried and re-weighed as described above.The amount of $PM_{2.5-10}$was determined by the difference in mass of the 2.5 µm filter papers before and after filtration.It was initially intended to examine both the $PM_{10}$ and $PM_{2.5}$ fractions, however, due to time constraints we were unable to do this and instead report the $PM_{2.5-10}$ fraction.

The total surface area of each sample was estimated by measuring the surface area of five random leaves from each sample, taking the mean, and multiplying by the number of leaves in the sample. The surface area of each leaf was determined by tracing its outline onto 0.25 $cm^2$ paper.

The density of $PM_{2.5\text{-}10}$ was calculated by dividing the mass of $PM_{2.5\text{-}10}$ of each sample, by the total surface area of each sample to give the 'surface density' of $PM_{2.5\text{-}10}$, measured in $g.m^{-2}$.

Hair density of each plant species was measured by randomly selecting a square centimetre on a single leaf of 10 separate random samples, and counting hairs under a 10 × magnification light microscope, and taking the mean of those counts for each species. Each species was then classified as being either glabrous, with a hair density of $< 100$ $cm^{-2}$ or with rough texture, or with hair density $> 100$ $cm^{-2}$.

*Statistical analysis*

Prior to analysis the data were tested to see if they met the assumptions of the linear model, andlog transformed. To test the difference in surface density of $PM_{2.5\text{-}10}$ between different plant species, the data were analysed using a linear model with 'species' fitted as the explanatory variable and'mean annual $PM_{10}$ ($\mu g.m^{-3}$)' as a covariable. To investigate the effect of different leaf surface characteristics on $PM_{10}$ capture, another linear model was fitted with the explanatory variables 'mean leaf surface area', 'hair density', and 'sampling month',and with the covariable'mean annual $PM_{10}$ ($\mu g.m^{-3}$)'. The maximal model was fitted then simplified to the minimal adequate model using backwards elimination of non-significant variables and comparison of models using analysis of variance (ANOVA).Post-hoc multiple comparisons were performed using Tukey's honest significant differences test. The ivy data was analysed using a paired *t*-test. The Lower Thames Street tower comparison was analysed using an unpaired *t*-test. All statistical analyses (including production of graphics) were performed using the software R 2.14.0 (R Development Core Team 2011) and the R package 'sciplot' (Morales 2010).

## Results

There was great disparity shown in the ability of different plant species to capture $PM_{2.5\text{-}10}$ (figure 1). One species, *Convolvulus cneorum* performed far better than any other species having a mean surface density of 2.73 (± 0.16, 1 standard error) $g.m^{-2}$. This was over 1.5× the next highest species, *Stachys byzantina* at 1.77 (± 0.16) $g.m^{-2}$ and almost 10× as high as the poorest performing species, *Hedera helix,* at 0.28 (± 0.02) $g.m^{-2}$.

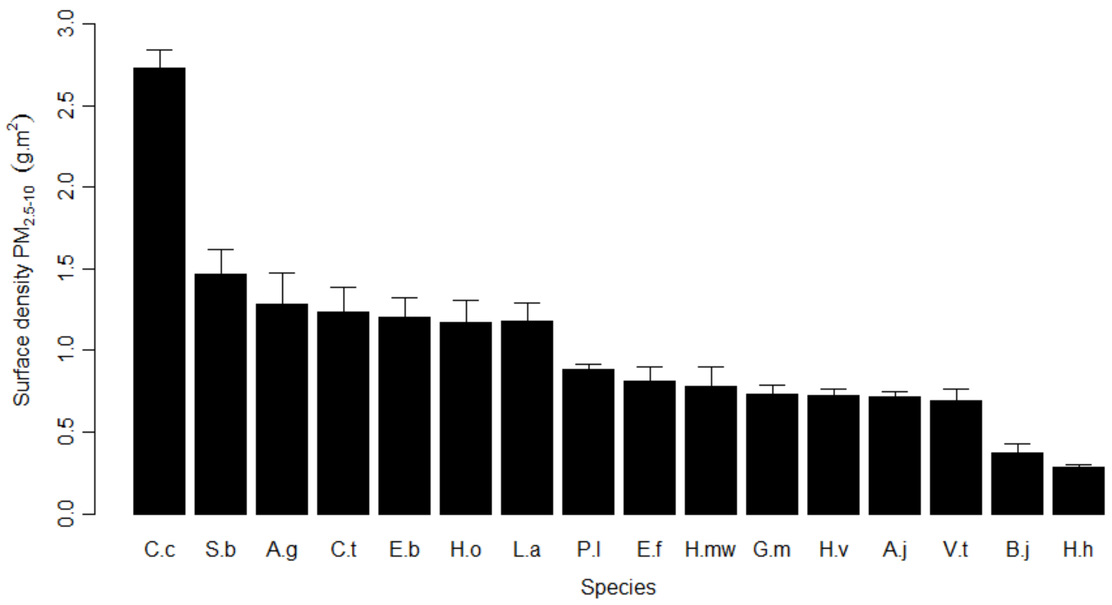


**Figure 1: Mean surface density of $PM_{2.5\text{-}10}$ capture across each plant species (± 1 standard error) -** ***C.c = Convolvulus cneorum, S.b = Stachys byzantina, A.g = AcorusGramineus, C.t = Carextestacea, E.b = Erysimumbicolor, H.o = Hebe odora, L.a = Lavendulaangustifolia, P.l = Prunuslaurocerasus, E.f = Euonymus fortune, H.mw = Hebe 'Mrs Winder',G.m = Geranium maculatum, H.v = Heucheravillosa, A.j = Aucuba japonica, V.t = Viburnum tinus, B.j = Berberisjulianae, H.h = Hedera helix.***

The best performing species tended to be those with the highest hair densities on the leaf surface, and smaller leaf surface areas (figures 2, 3). Plants with the highest hair density ( > 100 $cm^{-2}$) had captured significantly more $PM_{2.5\text{-}10}$ than either glabrous plants or those plants with lower hair densities($t = 8.08$, $p < 0.001$, d.f. = 496).($t = 4.70$, $p < 0.001$, d.f. = 496). This difference was very great, with those plants with hair densities > 100 $cm^{-2}$ capturing approximately double the amount of $PM_{2.5\text{-}10}$ than those plants which were glabrous (figure

2). Those plants with an intermediate hair density ($< 100$ cm$^{-2}$) also had significantly higher $PM_{2.5\text{-}10}$ capture efficiencies than glabrous plants ($t = 4.10$, $p < 0.001$, d.f. = 496) however, they were still far behind those plants with the highest hair densities (figure 2).

There was a significant trend for plants with small leaf surface areas to capture more particulates per unit surface area than those with larger leaves ($t = -6.89$, $p < 0.001$, d.f. 496, figure 3).

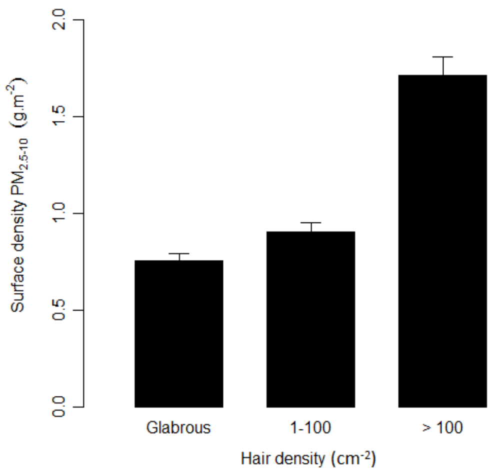


**Figure 2: The effect of hair density on particulate capture. Bars ± 1 S.E.**

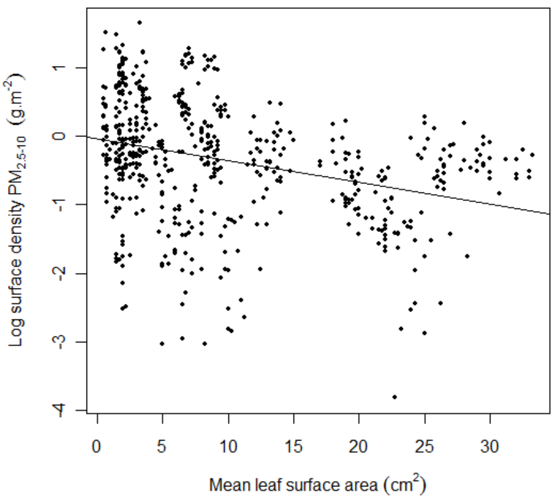


**Figure 3: The effect of mean leaf surface area on particulate capture. Line equation** ***$y = -0.03x + 0.003$.***

There was also a trend for plants to accumulate $PM_{2.5\text{-}10}$ over time during the sampling period (figure 4). Plants had significantly higher $PM_{2.5\text{-}10}$ in January than in December ($p < 0.001$) and plants in February also had significantly more $PM_{2.5\text{-}10}$ than in January ($p < 0.001$). Plants in March however, did not continue this trend and there was no significant difference in the $PM_{2.5\text{-}10}$ levels between February and March.

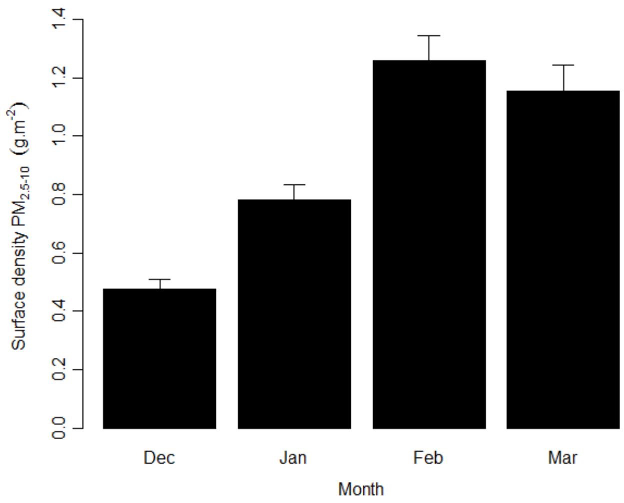


**Figure 4: The effect of time of $PM_{2.5\text{-}10}$ accumulation (± 1 S.E).**

For the second part of the study, orientation had no significant effect on $PM_{2.5\text{-}10}$ capture in ivy (figure 5). Ivy leaves collected from the road side of the plant did not have significantly different $PM_{2.5\text{-}10}$ surface densities than those on the pavement side (paired t-test, $t = 1.87$, $p = 0.069$, d.f. = 40). Figure 6 shows modelled ambient annual $PM_{10}$ concentrations for each site.

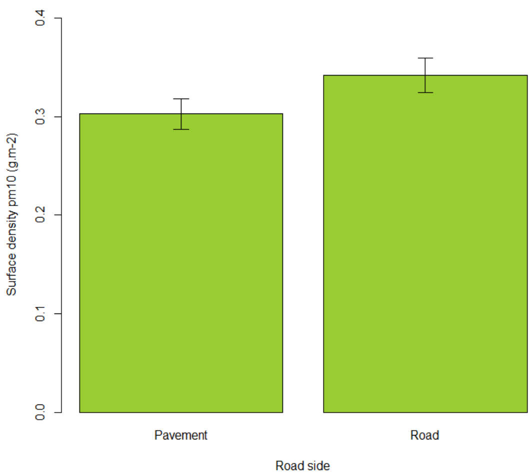


**Figure 5: The effect of plant orientation on $PM_{2.5\text{-}10}$ capture (± 1 S.E).**

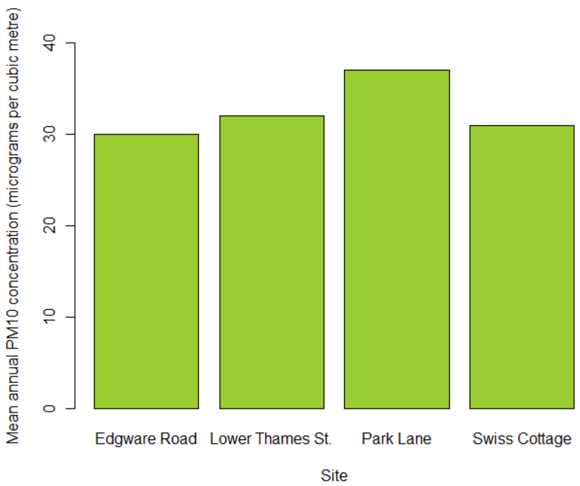


**Figure 6: Modelled ambient annual $PM_{10}$ concentrations.**

## Discussion

Particulate capture varied greatly across different plant species, with *Convolvulus cneorum* performing significantly better than all other species, and *Hedera helix* performing significantly worse than nearly all others. *C. cneorum* was in fact almost 10 × as efficient as *H. helix.*

It is however important to look at the efficacy as well as the efficiency of $PM_{2.5\text{-}10}$ capture. *Convolvulus cneorum* is a relatively small plant with the individuals in this study being less than half a metre in height and width and bearing a relatively small number of small leaves (mean surface area of 1.9 $cm^2$). The *H. helix* individuals were comparatively large ('planted towers' with plants nearly 2 m tall) and had very dense foliage of relatively large leaves (mean surface area of 21.9 $cm^2$). A simple calculation reveals than an individual *C. cneorum* leaf captures slightly less $PM_{10}$ than a *H. helix* leaf (0.0005 g compared to 0.0006 g) and therefore the particulate capture of an individual *H. helix* plant is likely to be much greater than a *C. cneorum* plant. It is therefore very important to consider these factors when planning urban greening projects (see further research section below).

Although the fraction of $PM_{10}$ below 2.5 µm was excluded from the present study, the values for $PM_{2.5\text{-}10}$ capture efficiency are similar to those from other studies. We report surface densities of $PM_{2.5\text{-}10}$ for different species in the range of 0.28 – 2.73 $g.m^{-2}$, compared to those reported in Beckett et al. (2000b) in the range of 0.1 – 0.5 $g.m^{-2}$ and those in Dzierzanowski et al. (2011) of 1.2 – 2.5 $g.m^{-2}$. While there are undoubtedly differences in the ambient $PM_{10}$ concentrations between the present study and those mentioned above owing to the different sampling locations (Brighton, England and Warsaw, Poland respectively), this similarity suggests two things: Firstly that shrubs are of comparable values to trees in terms of their particulate matter capture efficiency, if not their efficacy due to smaller size. Secondly that measuring $PM_{2.5\text{-}10}$ was not an unsuitable surrogate for measuring total $PM_{10}$.

Hair density was a primary factor in determining particulate capture. A higher density of hairs and a rougher surface will increase the available surface which can capture particulates. Those plants in the highest category of hair density (> 100 $cm^{-2}$) performed significantly better than all others. These included the two species most efficient at $PM_{2.5\text{-}10}$ capture; *C.*

*cneorum* and *Stachys byzantina*.Those with an intermediate hair density also performed significantly better than glabrous plants, although performed significantly worse than those in the highest category of hair density. That is not to say these trends was universal across all plants. For example the glabrous plant *Acorusgramineus* had significantly higher $PM_{10}$ capture efficiencies than plants such as *Geranium maculatum* which were in the intermediate hair density category.There was also a significant trend for plants with smaller leaves to capture more $PM_{2.5-10}$ per unit surface area and this relationship appeared approximately linear, at least in the range of leaf sizes in this study. Smaller leaved plants such as *C. cneorum* performed well while larger leaved plants such as *H. helix* and *Berberisjulianae*performed poorly. This is likely due to greater complexity in shoot structure associated with a plant with a greater number of small leaves causing greater disruption to the air flow surrounding it.

Two plants in the study were congeners; *Hebe odora* and *Hebe* 'Mrs Winder'. *Hebe odora* captured significantly more $PM_{2.5-10}$ than *Hebe* 'Mrs Winder', probably due to its smaller leaf size. It is interesting to note however that significant differences can occur between closely related plants with similar characteristics (both are glabrous with relatively small leaves).

Leaf shape is another potential factor affecting particulate capture, but it is much harder to measure quantitatively. It is interesting to note that the two species with a 'grass-like' structure and leaf shape, *Acorusgramineus* and *Carextestacea*, were two of the best performing species (neither are true grasses). It would be improper to draw any conclusion on the particulate capture efficiency of 'grass-like' species with only these two species represented in the present study, but further research is merited on other types of plant as tools for particulate mitigation as previous studies have looked at trees and this study has investigated shrubs. Theperformance of these two species may be explained by their relatively small leaf sizes although neither was in the highest category for hair density.

Plants also appeared to accumulate more particulates over time, with more captured in January than in December and more still in February than in January. This continual accumulation is probably symptomatic of the dry winter of 2011-2012, which likely resulted in a lack of wash off from the leaves. Although it is hard to draw strong conclusions from only four time points over a relatively short period, this suggests that plants do not get saturated with particulates immediately. It was only in the final sampling month (March) that leaf particulate levels did not increase further (they were not significantly different from February) suggesting that leaves were saturated with particulates. It is therefore likely that particulate accumulation will reach a plateau after a given period of time.

Monitoring this over a longer time period could prove difficult, as new bud and shoot growth begins in spring, and these new leaves will initially be free of any particulates so accumulation will begin again from zero. This is positive since the plant as a whole will continue to capture particulates beyond its initial saturation point due to its new leaf growth, but quantifying this accumulation would prove difficult.

Extended dry periods such as the winter of 2011-2012 may therefore hamper the removal of particulate from the air by vegetation, with a lack of wash-off allowing plants to become saturated with particulates. This however, may be alleviated by new growth in the spring and summer months.

Plant orientation had no significant effect on particulate capture on the ivy towers of Lower Thames St. It was thought that the side of the plant facing the road would capture more particulates than the side facing the pavement, and this would have meant that plants placed in the central reservation would have higher particulate capture potential than those on the roadside. This however, was not the case. It may be there is a small effect of orientation, but high ambient background levels of $PM_{2.5-10}$prevent any effect from showing.

*Wider benefits of green infrastructure*

While the main aim of green infrastructure under the CAF is to reduce particulate emissions, the wider benefits should also be considered. Urbanisation causes a loss of biodiversity through habitat destruction, degradation and fragmentation (Connor *et al.* 2002). Many cities contain green space in the form of urban parks, however, the management regimes are often curtailed to what human society deems aesthetically pleasing, recreational needs, and economic viability for governments (Sandstrom*et al*. 2006). Consequently, biodiversity is a low priority for urban planners and even where the desire to plan for biodiversity in cities exists, the knowledge to do so is often lacking (Sandstrom*et al*. 2006). Urban parks are therefore typified by short amenity grass with early successional species accompanied by mature trees, with very little existing in between (Snep*et al.* 2006, Niemelä 2011). The addition of flowering plants is a benefit to biodiversity, particularly birds and invertebrates, as flowers and berries provide important forage for pollinators and birds respectively. Plants native to Britain or Europe are likely to have the highest benefit to biodiversity. Organisms which are native to the same region as each other, have co-evolved such that animals can consume plants which they have co-evolved with more easily than those they have not. For example, a bird may not be able to digest the berries from a non-native plant as a native one. This is a general rule to which there are many exceptions.

Honeydew producing insects such as aphids are also supported by vegetation and may in fact provide a benefit to particulate capture. Aphids suck sap from the phloem of plants and secrete a sticky substance, honeydew, from the gut's terminal opening. A build-up of honeydew on the plant surface may help impacting particulates in the air to stick on to the plant, increasing capture efficiency. While the present study was winter-based, and the effect of honeydew was outside of the scope of the investigation (and any benefit of honeydew is likely to be observed in the summer months), aphids were observed on several plant species in the study including *Heucheravillosa, Geranium maculatum*and*Hedera helix*.

Urban areas are usually warmer than the surrounding landscape due to the urban heat island effect which has several causes (Raupp*et al.* 2009). Firstly, the impervious surface which has replaced vegetation absorbs more solar radiation and reradiates it back into the environment, secondly industrial processes and commercial premises produce excess heat, and thirdly the lack of vegetation and the rapid run off of water from the surface leads to less cooling from evapotranspiration than would normally occur (Raupp*et al.* 2009, Niemela 2011). Urban greening can therefore mitigate this problem by adding to the cooling effect of evapotranspiration and reducing the amount of impervious surface.

Biodiversity not only has intrinsic value, as the example above is just one such example of the ecosystem services biodiversity can provide. Globally, ecosystem services were valued at an average of $ 33 trillion (USD) compared to a global gross national product of $ 18 trillion (Costanza*et al.* 1997).

Green infrastructure also has positive effects on human wellbeing, improving mental health (Hansmann*et al.* 2007), encouraging physical activity (Ellaway*et al.* 2005) and promoting a general feeling of safety (Kuo& Sullivan 2001).

Aesthetics are very important for urban planners, and green infrastructure can improve the appearance of an area, therefore increasing the value of nearby properties (Luttik 2000).

*Future research into green infrastructure as a tool to mitigate air pollution*

**1) Experimental studies.** The present study can be improved upon through an experimental approach and would require collaboration with TFL. Picking several species of interest (based on the previous research), a balanced experimental design could be created to answer any number of questions on PM capture by vegetation. For example, questions on positioning of urban greening measures such as distance from the road or height up a wall.

The present study attempted to control for exposure to particulate matter sources as far as possible by standardising the sampling method and accounting for local $PM_{10}$ levels in the analysis. The ability to experimentally manipulate the locations and types of plantings would be of great benefit to understanding capture efficiencies. We were however, constrained in only being able to use green infrastructure already put in place.

**2) A cost-benefit analysis of urban greening measures.** Urban greening is not a cheap process and some projects such as green walls can venture into the hundreds of thousands of pounds (e.g. the Edgware Road wall). The question should be asked – How much benefit is there in terms of $PM_{10}$ capture (or any other given pollutant) or reduction (if it can be measured) given the monetary cost of a given urban greening project? E.g. Green walls vs. ivy towers vs. traditional shrub beds.

We also know that some plant species, or those with particular characteristics, are more efficient than others at capturing particulates. However, the most efficient individual plant may not be the most effective because it is small. Given that we know the capture efficiency of particulates for a number of plants, we can therefore calculate the capture efficiency in terms of monetary cost for those plants.

For example: The present study found that *Convolvulus cneorum* is more efficient than *Hedera helix*. But because a *H. helix* individual is larger, it will in fact remove more particulates from the air than an individual *C. cneorum*. The question is: How can I best spend a given amount of money to maximise particulate capture? How many *C. cneorum* plants can I buy for the price of one ivy tower, and which will capture the most particulates. The logistics of where and how many plants can be located will then also require consideration.

The cost-benefit analysis could be expanded to analyse different projects from the CAF as a whole – is urban greening value for money when measured against other methods aiming to reduce $PM_{10}$?

Urban greening measures should however be viewed in terms of their wider benefits. For example, while PM pollutants may be the primary driver behind urban greening from the CAF, greening also has other potential benefits, some of which are more easily quantified (e.g. biodiversity) than others (e.g. social wellbeing, raising environmental awareness). These should also be taken into account in a cost-benefit analysis.

**3) General expansion of the previous research.** The previous research was conducted on evergreen species on a few sites during a few winter months of one year. Further work could involve:

i) Comparison of evergreen species with deciduous species in the summer months and examination of the total annual benefit of each.
ii) Investigating the PM capture of green walls along a vertical gradient. Perhaps also including comparisons of green roofs with ground level vegetation.
iii) Investigation into $PM_{2.5}$ capture. Our studies have thus far only focused on the fraction of $PM_{2.5\text{-}10}$. However, $PM_{2.5}$ has also been shown to have adverse effects on human health. The work would be similar to the previous study but with different grades of filter paper to trap the appropriate fraction. Other air pollutants such as $NO_X$ could also be investigated with appropriate equipment.

**4) Investigation into other classes of vegetation.** Previous studies have focused on the role trees can play in particulate mitigation, whereas the present study has focused on shrub species. Interestingly however, two non-shrub, ‘grass-like’ species (*Acorusgramineus* and *Carextestacea*) were two of the best performing species, in spite of being glabrous. Further work could investigate how grasses, sedges, and other grass-like vegetation can be a tool to reduce air pollution. Other classes of vegetation such as mosses and lichens could also have their $PM_{10}$ capture potential tested.

**5) Calculations of the level of reduction of atmospheric pollution that can be expected from urban greening.** A very important unanswered question is ‘does urban greening actually lead to a reduction in atmospheric pollution?’ The mass of particulates (in grams) that green infrastructure measures can capture can be quantified as in this study, but how does this relate to the mass of particulates in London air (in terms of micro grams per cubic metre)?

## *Conclusions*

This study has quantified the capture efficiency of $PM_{2.5\text{-}10}$ for 16 plant species, revealing how some species perform exceedingly better than others, and how certain leaf surface characteristics are beneficial in aiding particulate capture. This study recognises the costs and trade-offs of implementing green infrastructure, but also the wider benefits to both human communities and the ecosystem as a whole that urban greening can provide.

Future green infrastructure projects should take into account multiple factors during planning including:
- The efficiency and efficacy of the plantings for particulate capture.
- The costs compared to the benefits of each measure.
- The positive effect on biodiversity and the ecosystem services provided.
- The positive effects on human health and wellbeing.
- The positive effects on human society as a whole.

## Acknowledgements

We would like to thank Transport for London for the funding and opportunity to perform this research, in particular Venn Chesterton and Nicola Cheetham were very helpful throughout. Paul Nicholas, Sally Power, Ellen Fry and Simon Leather of Imperial College London, Silwood Park Campus were very accommodating in providing laboratory space and materials for the work. Laura Hill of Imperial College London for providing modelled $PM_{10}$ data. The previous work of Hannah Smith also proved invaluable to the research. Lastly we would like to thank taxonomists of the Angela Marmot Centre of the Natural History Museum, London for help with plant identification.

## References:


*Directive 2008/50/EC.*(2008) European Parliament, EU

Beckett, K. P., Freer-Smith, P. H. & Taylor, G. (2000) Particulate pollution capture by urban trees: effect of species and windspeed. *Global Change Biology,* 6 (8), 995-1003

Connor, E.F., Hafernik, J., Levy, J., Moore, V.L., Rickman J.K. (2002) 'Insect conservation in an urban biodiversity hotspot: The San Francisco Bay Area', *Journal of Insect Conservation*, 6, 247-259

Costanza,R., d'Arge,R., de Groot,R., Farber,S., Grasso, M., Hannon,B., Limburg,K., Naeem,S., O'Neill, R.V., Paruelo, J., Raskin,R.G., Sutton, P.,van den Belt, M. (1997) 'The value of the world's ecosystem services and natural capital', *Nature,* 387, 253 - 260

Dockery, D. W. & Pope, C. A. (1994) Acute respiratory effects of particulate air pollution. *Annual Review of Public Health,* 15 (1), 107-132

Dzierżanowskia, K., Popeka, R., Gawrooskaa, H., Sæbøb, A. &Gawrooskia, S. W. (2011) Deposition of particulate matter of different size fractions on leaf surfaces and in waxes of urban forest species. *International Journal of Phytoremediation,* 13 (10), 1037-1046

Ellaway, A., Macintyre, S. &Bonnefoy, X. (2005) Graffiti, greenery, and obesity in adults: secondary analysis of European cross sectional survey.*BMJ,* 331 (7517), 611-612

Freer-Smith, P. H., Beckett, K. P. & Taylor, G. (2005) Deposition velocities to Sorbus aria, Acer campestre, Populusdeltoides × trichocarpa 'Beaupré', Pinusnigra and × Cupressocyparisleylandii for coarse, fine and ultra-fine particles in the urban environment. *Environmental Pollution,* 133 (1), 157-167

GLA. (2002) *Cleaning London's air: The Mayor's Air Quality Strategy.* London, Greater London Authority

GLA. (2010) *Cleaning the air: The Mayor's Air Quality Strategy.* London, Greater London Authority

Hansmann, R., Hug, S. M. &Seeland, K. (2007) Restoration and stress relief through physical activities in forests and parks.*Urban Forestry & Urban Greening*, 6 (4), 213-225

Krzyzanowski, M. & Cohen, A. (2008) Update of WHO air quality guidelines.*Air Quality, Atmosphere & Health*, 1 (1), 7-13

Kuo, F. E. & Sullivan, W. C. (2001) Environment and Crime in the Inner City.*Environment and Behavior*, 33 (3), 343-367

Lovett, G. M. & Lindberg, S. E. (1992) Concentration and deposition of particles and vapors in a vertical profile through a forest canopy.*Atmospheric Environment*, 26 (8), 1469-1476

Luttik, J. (2000) The value of trees, water and open space as reflected by house prices in the Netherlands. *Landscape and Urban Planning,* 48 (3-4), 161-167

McDonald, A. G., Bealey, W. J., Fowler, D., Dragosits, U., Skiba, U., Smith, R. I., Donovan, R. G., Brett, H. E., Hewitt, C. N. &Nemitz, E. (2007) Quantifying the effect of urban tree planting on concentrations and depositions of PM10 in two UK conurbations. *Atmospheric Environment*, 41 (38), 8455-8467

Morales, M. (2010).sciplot: Scientific Graphing Functions for Factorial Designs. R package version 1.0-7.http://CRAN.R-project.org/package=sciplot

Niemela, J. (2011) *Urban Ecology – Patterns, Processes and Applications* (1st edition) Oxford University Press

R Development Core Team (2011) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org

Sandstrom, U.G., Angelstam, P., Khakee, A. (2006) ‘Urban comprehensive planning - identifying barriers for the maintenance of functional habitat networks’, *Landscape and Urban Planning*, 75, 43-57

Smith, H. (2011) 'The use of vegetation to mitigatie particulate pollution in urban environments: a technique for London to meet one of its air pollution targets?', unpublished Master's thesis, Imperial College London

Snep, R.P.H., Opdam, P.F.M., Baveco, J.M., Wallis De Vries, M.F., Timmermans, W., Kwak, R.G.M, Kuypers, V. (2006) 'How peri-urban areas can strengthen animal populations within cities: A modeling approach', *Biological Conservation*, 127, 345-355

WHO. (2006) *Air quality guidelines: Global Update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide.*Copenhagen, World Health Organisation

Williams, M. L. (2000) Atmospheric pollution: contribution of automobiles. *Revue Françaised'AllergologieEtd'Immunologie Clinique,* 40 (2), 216-221

Zanobetti, A., Schwartz, J., Samoli, E., Gryparis, A., Touloumi, G., Peacock, J., Anderson, R. H., Le Tertre, A., Bobros, J. &Celko, M. (2003) The temporal pattern of respiratory and heart disease mortality in response to air pollution. *Environmental Health Perspectives,* 111 (9), 1188

## Appendix I: Total $PM_{2.5\text{-}10}$ capture of the Edgware Road green wall.

Using data collected in the main study, and knowing the total number of plants of each species planted on the Edgware Road wall, its total $PM_{2.5\text{-}10}$ capture can be calculated using equation 1 below. The results are summarised in table 4.

For each plant species:

No. plants × Mean no. leaves per plant × Mean leaf surface area × Mean surface density $PM_{2.5\text{-}10}$

Or

$$\sum n_p n_l S P$$

Eqn. 1

Assumptions and caveats:

- This calculation is based on the 3 month period between 28$^{th}$ November and 24$^{th}$ February.
- Number of leaves based upon the mean of 10 random samples from each species taken on 18/05/2012.
- Assumes equal particulate capture along the vertical gradient of the wall (measurements were taken between 0.5 – 2.0 m).
- Assumes number of leaves per plant remains constant over the sampling period.
- Values based on data collected in winter. Particulate capture potential may be higher in spring and summer when new leaf growth occurs and total plant surface area is greater.
- For species not sampled in initial study, values are estimated based upon their leaf surface characteristics using the linear model in the main body of the study (8 / 15 species were sampled in the main study, with the second variety of *Euonymus fortune* being assumed to behave identically to the first).
- This is likely an underestimate since some particulates will wash off due to precipitation.
- Only takes into account leaf particulate capture, not stems or flowers.
- The fraction of $PM_{10}$ below 2.5 µm is omitted resulting in an underestimate.

**Table 4: Calculation of total $PM_{2.5-10}$ capture by the Edgware Road green wall.**

| Species | No. plants | No. leaves | Mean leaf surface area ($cm^2$) | Surface density $PM_{2.5-10}$ ($g.cm^{-2}$) | Total $PM_{2.5-10}$ capture (g) |
|---|---|---|---|---|---|
| *Stachys byzantina* | 548 | 27.6 | 8.88 | 0.000293 | 39.33 |
| *Geranium maculatum* | 779 | 12.2 | 16.57 | 0.000112 | 17.64 |
| *Heucheravillosa* | 1184 | 7.6 | 21.03 | 0.000070 | 13.24 |
| *Carextestacea* | 1230 | 134.0 | 4.81 | 0.000219 | 173.62 |
| *Acorusgramineus* | 513 | 51.2 | 6.81 | 0.000304 | 54.38 |
| *Erysimumbicolor* | 779 | 68.4 | 3.41 | 0.000122 | 22.17 |
| *Euonymus fortunei* * | 856 | 59.4 | 2.42 | 0.000151 | 18.58 |
| *Lavendulaangustifolia* | 989 | 219.6 | 1.72 | 0.000158 | 59.02 |
| *Lonicerapileata* | 642 | 143.0 | 0.50 | 0.000124 | 5.69 |
| *Veronica sp.* | 1107 | 202.0 | 0.63 | 0.000176 | 24.6 |
| *Vinca minor* | 1292 | 28.0 | 2.25 | 0.000117 | 9.52 |
| *Waldsteiniaternata* | 1292 | 19.4 | 7.50 | 0.000142 | 26.69 |
| *Euphorbia sp.* | 420 | 76.8 | 5.50 | 0.000106 | 18.81 |
| *Unknown species* ** | 1117 | 25.6 | 10.25 | 0.000109 | 31.95 |
| | | | | **Grand total:** | **515.24** |

* Includes both *Euonymus fortunei* varieties. ** Listed as *Hypericumcalycinum* but is in fact a different species.

The question now remains as to whether 515 g of $PM_{10}$ reduction over 3 months represents value for money (bearing in mind this is likely an underestimate, see caveats above).

## Appendix II: Comparison of *Geranium maculatum* and *Hedera helix* towers on Lower Thames Street.

In October of 2011, *Geranium maculatum* towers were present on Lower Thames Street in place of the current *Hedera helix* towers. The *G. maculatum* towers formed the basis of some preliminary research. Using that data collected in October 2011, we formed a comparison of *G. maculatum* towers (n = 50) with *Hedera helix* (n = 41) tower data collected in March 2012.

Surprisingly, the *Hedera helix* towers at Lower Thames Street had significantly greater capture efficiency than *Geranium maculatum* towers ($t$ = 4.33, d.f = 87, $p < 0.001$, figure 6). This is in direct contrast to the overall species comparison (figure 1) where *G. maculatum* from Edgware Road had significantly higher $PM_{2.5\text{-}10}$ capture efficiency than *H. helix*. This would also mean that the *G. maculatum* towers were the least efficient plants at $PM_{2.5\text{-}10}$ capture in the entire study. There are however other factors to consider, primarily the five month period between *G. maculatum* and *H. helix* samples being taken. Factors such as variation in climate, particularly the dry period when *H. helix* was sampled, could have had an impact.

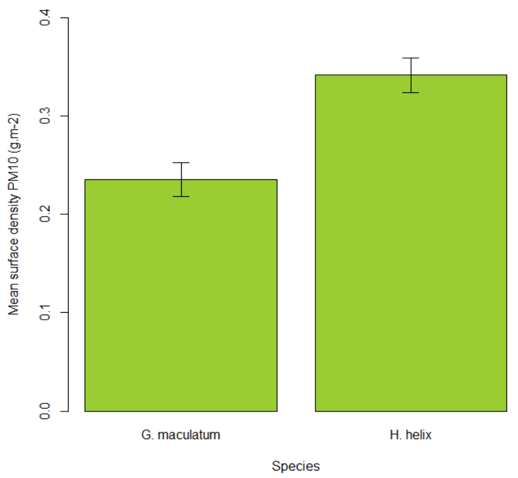


**Figure 6: Comparison of *Geranium* and ivy towers on Lower Thames St. (± 1 S.E).**