

Air Quality Considerations for Stormwater Green Street Design

Kathryn M. Shaneyfelt^{a*}, Andrew R. Anderson^b, Prashant Kumar^c, and William F. Hunt III^a

^aDepartment of Biological and Agricultural Engineering, North Carolina State University, Box 7625, Raleigh, NC 27695, United States

^bHazen and Sawyer, One South Broad Street, Suite 1630, Philadelphia, PA 19107, United States

^cGlobal Centre for Clean Air Research (GCARE), Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, United Kingdom

*Corresponding author, kmconroy@ncsu.edu

Graphical abstract



Abstract

Green streets are increasingly being used as a stormwater management strategy to mitigate stormwater runoff at its source while providing other environmental and societal benefits, including connecting pedestrians to the street. Simultaneously, human exposure to particulate matter from urban transportation is of major concern worldwide due to the proximity of pedestrians, drivers, and cyclists to the emission sources. Vegetation used for stormwater treatment can help designers limit the exposure of people to air pollutants. This goal can be achieved through the deliberate placement of green streets, along with strategic planting schemes that maximize pollutant dispersion. This

26 review presents general design considerations for green streets that combine stormwater management
27 and air quality goals. There is currently limited guidance on designing green streets for air quality
28 considerations; this is the first review to offer suggestions and advice for the design of green
29 stormwater streets in regards to their effects on air quality. Street characteristics including (1) the
30 width to height ratio of the street to the buildings, (2) the type of trees and their location, and (3) any
31 prevailing winds can have an impact on pollutant concentrations within the street and along
32 sidewalks. Vegetation within stormwater control measures has the ability to reduce particulate matter
33 concentrations; however, it must be carefully selected and placed within the green street to promote
34 the dispersion of air flow.

35 **Keywords:** Green Streets; Stormwater; Air Quality; Street Trees; Particulate Matter

36

37 Highlights

- 38 • Green streets can be used for both stormwater and air quality management.
- 39 • Design considerations must be made to minimize human exposure to air pollutants.
- 40 • Urban vegetation can improve air quality with careful selection and placement.

41

42 Introduction

43 Urbanization is a major demographic trend in the 21st century, with an estimated 54% of the world's
44 population living in urban areas today (UN 2015). A key land use development activity associated
45 with urbanization is construction of impervious surfaces such as roadways, driveways, buildings, and
46 parking lots. Impervious cover leads to increased stormwater volumes, higher peak flows, and larger
47 pollutant loads entering receiving water bodies (James 1965; Leopold 1968), with as little as 5%
48 impervious cover in a watershed being correlated with the start of stream degradation (Schueler et
49 al. 2009). Concurrently, air pollution is a major public health problem worldwide (Kumar et al. 2015,
50 2016). In urban areas more than 80% of people are exposed to air pollutant levels that exceed limits
51 set by the World Health Organization (WHO 2016). Outdoor air pollution was estimated to cause
52 3.7 million premature deaths worldwide, with mortality linked to exposure to particulate matter ≤ 10
53 μm in diameter (PM₁₀) (WHO 2014).

54

55 Transportation corridors constitute one of the largest categories of impervious land uses in urban
56 areas, comprising 28% of all impervious area in an analysis of six urban and sub-urban watersheds
57 in the United States (Tilley and Slonecker 2006), nearly equivalent to the 29% of area occupied by
58 buildings. An analysis of 20 major cities in Europe, North America, and Oceania showed an average

59 of 26% city core land allocated to streets, ranging from Moscow and Auckland (14 and 18%,
60 respectively) to Toronto and New York City (34 and 36%, respectively) (UN Habitat 2013).
61 Roadways dramatically impact hydrology and water quality because they typically directly connect
62 impervious areas, resulting in the rapid conveyance of pollutants such as sediment, heavy metals,
63 nutrients, bacteria, and oils and greases without opportunity for removal (US EPA 2007). Because
64 (1) the right-of-way transportation corridor is often the jurisdiction of a city and (2) of its
65 preponderance to discharge high volumes of stormwater per mm of rainfall vis-à-vis other land uses,
66 many municipalities see the roadway as an opportunity to reduce stormwater volume. Moreover,
67 motor traffic using these roadways is one of five major anthropogenic sources of air pollution (along
68 with industry, power plants, trade, and domestic fuel) (Mayer 1999). Road traffic emissions of
69 particulate matter have several sources including exhaust, brake wear, and tire wear emissions along
70 with the resuspension of road dust from moving vehicles (Charron and Harrison 2005). The focus of
71 this review is to link these two environmental and societal challenges—increased stormwater runoff
72 and air pollution—in the guise of a transportation corridor known as a “green street,” which will be
73 defined later in this review.

74

75 *Traditional Roadway Design*

76 Historically, roadway design has focused almost exclusively on automobile transportation. The
77 primary goals of roadway design in urban areas are motorist and pedestrian safety, levels of service,
78 and flow capacity (vehicles per unit time per lane). Resultant design parameters of these goals include
79 speed limits, horizontal and vertical curvature, parking incorporation, street width, and lane width
80 (Lindeburg 2014). More hydraulically-efficient designs minimize the spatial and temporal extent of
81 water spread, and therefore improve motorist safety.

82

83 *Complete Streets and Green Streets*

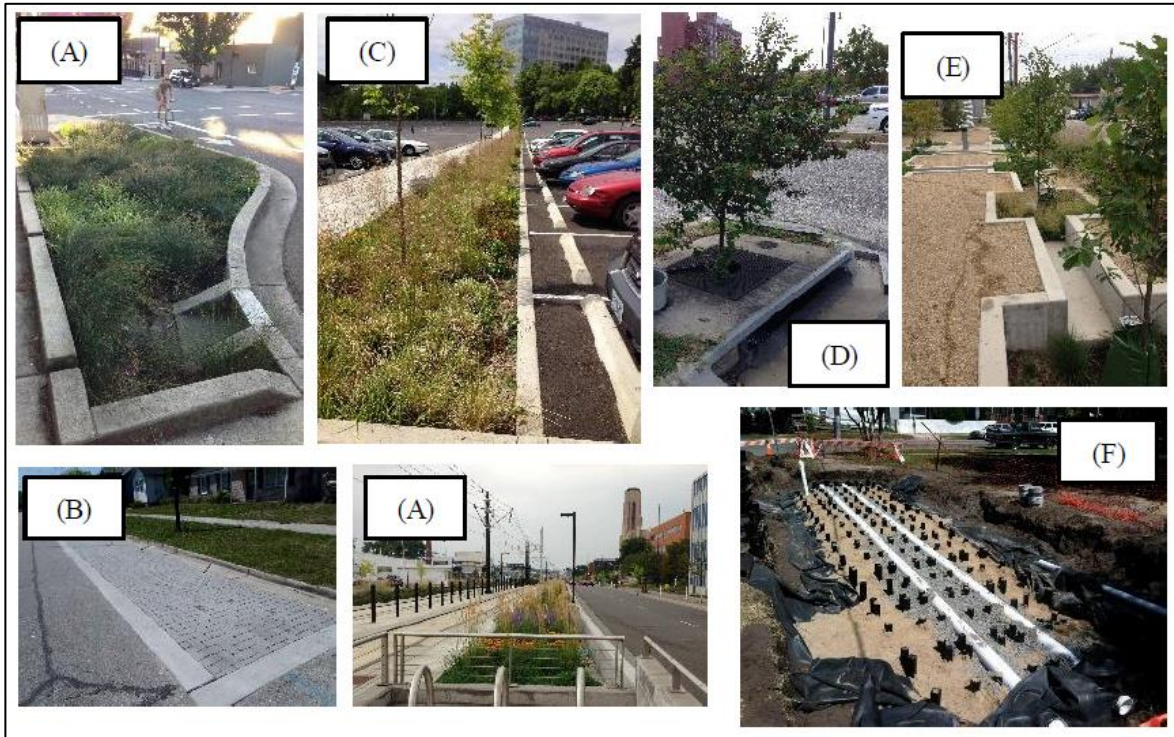
84 A broad design term used by urban planners is “complete streets”. This encompasses the holistic
85 planning of multi-modality transportation corridors, promoting safe, convenient, and comfortable
86 travel for cyclists, pedestrians, and vehicles. “Green streets” are often defined to meet environmental,
87 aesthetic, and quality of life goals under the larger umbrella of complete street design. To date, over
88 300 jurisdictions in the United States have adopted some form of Complete Streets policy (UN
89 Habitat 2013). Green streets with respect to stormwater treatment are much newer, as they are
90 developmentally linked with the increasing concern over water quality starting in the early 1990s in
91 the United States. “Green streets” refer to transportation corridors in which low impact development

92 (LID, Fletcher et al. 2015) is employed as a design principle by using a variety of green stormwater
93 infrastructure (GSI) practices to treat direct transportation surface drainage in the right-of-way. In
94 addition to structural control measures, green streets can also be characterized by impervious-
95 reducing design measures such as narrower road sections. Of the seventeen North American
96 jurisdictions with official green streets programs found by the authors, all but one included
97 stormwater treatment as a primary goal in its definition of “green streets”. While a green street may
98 employ green amenities (plants and landscaping), the principle of “green” in the street design sense
99 generally refers to preserving environmental quality. Many cities seek a holistic purpose for green
100 street design, defining green streets as ecosystems that “are part of the natural landscape” (City of
101 Austin 2015), increase safety and walkability, improve air quality and minimize the urban heat island
102 effect (City of Philadelphia 2014), and provide attractive landscapes while enhancing neighborhood
103 livability (City of Pamaona 2014).

104

105 Green streets typically involve combinations of stormwater control measures (SCMs) and road
106 design practices to reduce runoff. The most common SCMs used in the right-of-way include
107 bioretention, bioswales, vegetation planter filtration/infiltration boxes, permeable pavement, and
108 suspended pavement street tree systems (Figure 1). Bioretention cells are shallow, vegetated
109 depressions containing engineered soil media, often with underdrains 0.6 – 1.2 m below the surface
110 (Hunt et al. 2012). Bioretention / bio-infiltration has been studied for stormwater pollutant removal
111 since the early 2000s, showing the ability to infiltrate the majority of small rainfall events (Brown
112 and Hunt 2011; Davis et al. 2009; Asleson et al. 2009; Shuster et al. 2007) as well as remove many
113 common urban pollutants (Davis et al. 2009). Permeable pavement infiltrates direct rainfall or run-
114 on from other impervious surfaces (Eisenberg et al. 2015), resulting in potentially significant volume
115 reduction (Wardynski et al. 2013; Fassman and Blackbourn 2010) and pollutant sequestration (Bean
116 et al. 2007; Brown et al. 2015). Suspended pavement street systems use un-compacted soil
117 underneath sidewalks or streets that have one or more full-canopy trees that can access this soil that
118 is fed with stormwater runoff. A suspended pavement street tree stormwater system with sub-grade
119 soil storage in North Carolina, USA, showed mass load reductions for total phosphorus, total
120 suspended solids, copper, lead and zinc of 91%, 54%, 88%, and 77%, respectively (Page et al.
121 2015a). The presence of full-canopy street trees alone can reduce stormwater volumes and pollutant
122 loads through canopy interception (Lormand 1988; Xiao et al. 1998; Inkiläinen et al. 2013). Only
123 components of green streets (rather than the entire green street) have been extensively monitored and
124 published as peer-reviewed studies (Table 1). Individually, the SCMs show promise, reducing total
125 volumes, pollutant concentrations and loads. SCMs are the practices designers can modify to not

126 only meet hydrologic and water quality needs, but also to answer other environmental challenges
127 (such as air quality).
128



129
130 **Figure 1.** Common stormwater control measures used on green streets. (A) Bioretention, (B)
131 permeable pavement (specifically permeable interlocking concrete pavers), (C) bioswale, (D)
132 biofiltration unit, (E) tree planter infiltration boxes, (F) suspended pavement street tree soil storage
133 before final surfacing and tree planting.

134
135 Cost is often a barrier for green street implementation, affecting how and when to retrofit. Seattle,
136 Washington’s “SEA” street added traffic calming features to 0.40 lane-kilometers (treating 0.93 ha)
137 of a residential access road, by adding right-of-way vegetation and permeable pavement, cost US\$
138 1.14 million when adjusted for inflation in 2015 (Horner et al. 2002). This retrofit completely
139 captured an estimated 93% of rainfall events relative to pre-construction (Horner et al. 2002). In
140 contrast, a 0.54 lane-km (0.53 ha) retrofit on a residential road in Wilmington, NC, USA cost an
141 estimated \$85,000 USD for two bioretention cells, two permeable pavement parking sections, and
142 one tree filter box, resulting in a mean runoff depth decrease of 52% (Page et al. 2015b). Other
143 projects’ costs have ranged from \$314,000 (in 2016 dollars) (Seattle, Washington, Horner 2004) to
144 \$15.8 million (Atlanta, Georgia, Shamma 2015). Costs vary per many factors, including the type and
145 quantity of SCM employed. The justification of the extra expenditure of green street retrofits can be

146 bolstered by accounting for multiple streams of benefits, especially those outside of runoff and water-
147 borne pollutant mitigation (Moore and Hunt 2012).

148

149 *Other Benefits of Green Streets*

150 As evident in the definition of green streets by major municipalities, benefits other than stormwater
151 management are expected and planned for. Urban vegetation provides shade and evapo-
152 transpirational cooling, helping mitigate the urban heat island effect (Norton et al. 2015; Solecki et
153 al. 2005). Napoli et al. (2016) found negative correlations between measured asphalt surface
154 temperature in the shade of urban trees and the leaf area index of the trees themselves. Ward et al.
155 (2008) found that properties in Seattle abutting four well-known green street projects sold for 3.5 to
156 5% more during the period after the adjacent streets were built, controlling for similar square footage,
157 building quality, and lot size. Groundwater recharge increase has been observed with green
158 infrastructure use (Girling and Kellett 2005; Council for Watershed Health 2010).

159

160 As practitioners begin to think holistically about meeting multi-phase goals of green streets other
161 than traffic patterns and drainage design, more comprehensive data are needed on ancillary benefits
162 that go into specific design decision. As green street goals specifically include attracting pedestrians
163 and cyclists to the streetscape, the interaction between vehicular emissions and human exposure
164 becomes evident. Therefore, it is in the interest of planners and engineers to consider the air quality
165 impacts of putting vegetation in the right-of-way, as is the practice with green street implementation.

166

167 *Air Quality vis-à-vis Green Streets*

168 Persistent urbanization, a rising world population, and an increasing rate of car ownership (Dargay
169 et al. 2007) leads to a growing number of people being exposed to air pollution (Baldauf et al. 2013).
170 The ‘green’ part of green streets – trees and vegetation – could assist in improving air quality and
171 reducing individual’s exposure to unhealthy pollutants in the urban air (Nowak et al. 2006; Tiwary
172 et al. 2009). Urban plants, including individual trees, herbaceous vegetation, and forests, have been
173 shown to accumulate particulate matter from the atmosphere (Table 2, Nowak 1994; Freer-Smith et
174 al. 1997; McDonald et al. 2007; Dzierżanowski et al. 2011). In addition to stormwater management
175 goals, designers of green streets should attempt to minimize the exposure of people to harmful
176 pollution by maximizing the dispersion of pollutants (Oke 1988).

177

178 Exposure to particulate matter in urban areas can increase the risk of numerous negative health
179 effects, including cardiovascular and respiratory diseases and lung cancer (WHO 2016). Fine

180 particulate matter, which refers to particles $\leq 2.5 \mu\text{m}$ in diameter ($\text{PM}_{2.5}$), is especially harmful to
181 humans because these particles can lodge deeply into the lungs upon inhalation, with some
182 penetrating into the alveoli of the lungs (Samet et al. 2000; Heal et al. 2012; US EPA 2016). While
183 cycling and walking are encouraged in cities around the world as a healthy and sustainable mode of
184 transport, active commuters are receiving higher pollution doses than individuals using motorized
185 transport (Colvile et al. 2001; Gulliver and Briggs 2007; Panis et al. 2010; Dirks et al. 2012).

186

187 Urban ‘hot-spots’ of poor air quality can include traffic intersections, busy roadsides, and street
188 canyons (Goel and Kumar 2014). Higher levels of traffic emissions and restricted natural ventilation
189 can lead to elevated pollutant concentrations at these hot-spots (Ahmad et al. 2005). Particulate
190 matter concentrations in urban areas can be reduced by lowering their emission, increasing
191 dispersion, and/or improving deposition rates (Pugh et al. 2012). Using strategically planned
192 vegetated SCMs and street trees within green streets to filter, intercept, deposit, and absorb both the
193 $\text{PM}_{2.5}$ and PM_{10} will help improve the life expectancy of citizens in urban areas (Pope et al. 2009).
194 When examining the particulates (quantity, morphology, and elemental analysis of particles) present
195 on tree leaves, urban trees have been found to remove particulate matter from the atmosphere (Freer-
196 Smith et al. 1997; Beckett et al. 2000c). Additionally, researchers have determined that trees closer
197 to busy roads capture more particulate matter than those farther from the road (Beckett et al. 2000b;
198 Mori et al. 2015). Nowak et al. (2014) predicted that trees and forests in urban areas within the
199 conterminous United States removed an estimated 27,000 tonnes of $\text{PM}_{2.5}$ in 2010 with an associated
200 removal value of \$3.1 billion in regards to human health. The ability of green streets to improve air
201 quality is dependent on the vegetation present (species, age, porosity, number of plants, location),
202 the climate (in-leaf season, precipitation amounts, wind speeds, relative humidity), the location of
203 the SCMs relative to the emission source, and the characteristics of the street and pollution (Nowak
204 et al. 2006; Buccolieri et al. 2009; Gromke and Ruck 2012).

205

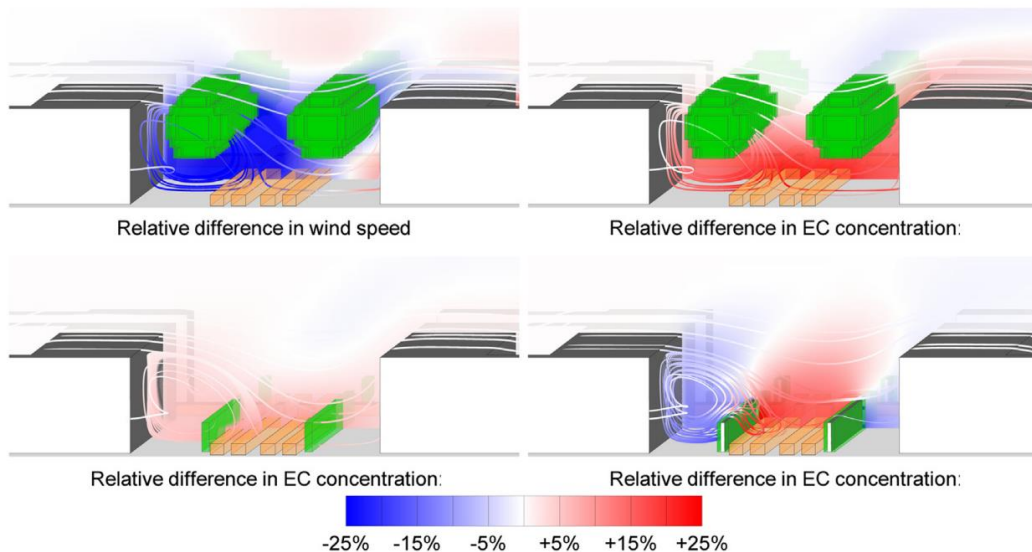
206 **Vegetation and Particulate Matter Interactions**

207 Reducing the concentration of particulate matter in the atmosphere through interception, filtration,
208 deposition, and absorption is a valuable ecosystem service provided by urban vegetation (Nowak et
209 al. 2006; Yan et al. 2016). Vegetation types ranging from trees, shrubs, grasses, herbs, and climbers
210 have been shown to accumulate particulate matter and act as air pollutant sinks (Beckett 2000c;
211 Dzierżanowski et al. 2011; Weber et al. 2014). Brownian diffusion is the primary deposition
212 mechanism for ultrafine particles (those less than $0.1 \mu\text{m}$ in diameter), while interception and

213 impactation are the mechanisms that remove most fine (those $\leq 2.5 \mu\text{m}$ in diameter) and coarse (those
214 between 2.5 and $10 \mu\text{m}$) particulate matter (Hinds 1999; Lorenzini et al. 2006). Other characteristics
215 that can affect the deposition of particulate matter onto vegetation include the particle shape; the
216 location, shape, size, and porosity of vegetation present; and the temperature, relative humidity, and
217 wind speed (Buccolieri et al. 2009). Nowak et al. (2014) predicted that trees and forests in urban
218 areas within the conterminous United States removed approximately 27,000 tonnes of $\text{PM}_{2.5}$ from
219 the atmosphere in 2010, while Jim and Chen (2008) estimated that urban trees within the city
220 removed 107 Mg of total suspended particulates in one year in Guangzhou, China.

221

222 While urban vegetation is often positively promoted as a method to improve air quality (McPherson
223 et al. 1994; Beckett et al. 1998; Nowak 2002), many studies have shown that adding vegetation,
224 especially trees, to hot-spots of air pollution (e.g., poorly ventilated areas along streets) can increase
225 pollutant concentrations by further restricting air flow and exchange (Gromke and Ruck 2007;
226 Buccolieri et al. 2009; Tiwary and Kumar 2014) (Figure 2). This highlights the need for smart urban
227 planning and a more thorough understanding of the best placement for various green infrastructure
228 systems.



229

230 **Figure 2.** Example of vegetation's impact on air flow and pollutant concentrations in street
231 canyons. Source: Vos et al. 2013.

232

233 *Street Trees*

234 Trees are considered the most efficient plant for particulate matter removal due to their large leaf
235 surface area (Nowak 1994) and the turbulent mixing produced by the air passing through and over

236 them (Beckett et al. 2000a). The removal of particulates from the atmosphere by plants occurs
237 throughout the day and year-round through the interception of particulates by plant leaves and bark
238 on trees (Nowak et al. 2006). However, certain seasons can have higher rates of particulate matter
239 deposition than others, dependent upon vegetation types, pollutant emissions, and meteorological
240 conditions (Nowak et al. 2006; Jim and Chen 2008; Schaubroeck et al. 2014). Also, particulate matter
241 capture increases with higher wind speed (Beckett et al. 2000a; Nowak et al. 2013) and likely changes
242 throughout the day (Nguyen et al. 2015). Additionally, trees placed near heavily trafficked roadways
243 collect more particulate matter as compared to trees near less trafficked roadways (Beckett et al.
244 2000b; Mori et al. 2015). The size of the tree can also have an impact on its ability to trap particulate
245 matter and other pollutants. Trees with diameters greater than 76 cm were predicted by Nowak (1994)
246 to remove 1.4 kg of pollution per year, whereas, trees with diameters less than 8 cm were predicted
247 to remove 0.02 kg of pollution per year. This increase in pollution removal rates for larger trees is
248 attributed to their high leaf surface area compared to that of smaller trees. Hofman et al. (2014)
249 looked at leaf density of tree crowns and particle deposition using Light Detecting and Ranging
250 (LiDAR) data and demonstrated that an increase in leaf density decreased the deposition of particles.
251 Nevertheless, the researchers asserted that the effect of leaf density on particle deposition was low
252 compared to other tree characteristics including height and position (Hofman et al. 2014).

253

254 Although urban trees can provide extensive ecosystem services, the placement of street trees within
255 street canyons can lead to localized increases in particulate matter concentrations (Gromke and Ruck
256 2007, 2009, 2012; Gromke et al. 2008; Buccolieri et al. 2009, 2011; Wania et al. 2012; Jin et al.
257 2014). An urban street canyon is a “relatively narrow street between buildings which line up
258 continuously along both sides” (Nicholson 1975). Vardoulakis et al. (2003) suggested that an urban
259 street having a width to height ratio of the street to the buildings equal to 1 may be called a regular
260 street canyon. Jeanjean et al. (2015) performed computation fluid dynamic simulations of air
261 pollutants using LiDAR data on buildings and trees in the city center of Leicester, UK. The
262 researchers found that trees reduced air pollutants from traffic emissions by an average of 7% at
263 breathing level for pedestrians due to an increase in turbulence; however, they also found that trees
264 significantly increased the concentrations of traffic emission pollutants in deep street canyons. Street
265 canyons with avenue-like tree plantings have reduced air flow velocities, inhibited air ventilation,
266 and reduced dispersion and dilution (all of which lead to increased pollutant concentrations)
267 compared to tree-free street canyons (Buccoleiri et al. 2009; Gromke et al. 2009; Gromke and Ruck
268 2012).

269

270 *Roadside Vegetation Barriers*

271 Vegetation barriers can be placed along roads as an attempt to improve air quality, reduce noise
272 pollution, or for purely aesthetic reasons (Al-Dabbous and Kumar 2014). Green barriers are defined
273 by Vos et al. (2013) as “a solid (impermeable) screen covered with hedge-like vegetation at both
274 sides.” Both hedges and green barriers were found to reduce the wind speed within the street canyon,
275 leading to higher pollutant concentrations in the driving lanes than in a street canyon with no
276 vegetation (Vos et al. 2013). The green barriers did shelter the pedestrians from increased pollutant
277 concentrations and improved the air quality on the sidewalk (Vos et al. 2013), while the hedges (due
278 to their porosity) did not. However, a roadside vegetative barrier in Surrey, UK, was found to reduce
279 the particle number concentration along the sidewalk during cross-road winds by 37% when
280 compared to a vegetation-free location. These studies emphasize the need for further research on
281 vegetation barriers to determine optimal design specifications (i.e., placement, vegetation types,
282 barrier widths) for improving air quality along roadways, and also to investigate their (probably)
283 modest stormwater mitigation benefits associated with interception.

284

285 *Vegetation Efficiencies*

286 Particulate matter removal depends on the species present (leaf type, angle, size, in-leaf season),
287 plant placement, meteorological conditions (wind speed, precipitation, relative humidity), and the
288 pollutant concentrations and emission sources (Beckett et al. 1998; Nowak et al. 2006; Litschke and
289 Kuttler 2008; Buccolieri et al. 2009). Trees are the most efficient vegetation type at removing
290 particulate matter due to the turbulence in air flow they cause as well as their large leaf surface areas
291 (Beckett et al. 2000a)

292

293 For individual trees, both coniferous and broadleaf species have shown the ability to collect large
294 amounts of particulate matter; however, coniferous trees are more effective than broadleaf trees due
295 to their more complex shoot structure and fine needles (Beckett et al. 2000a; Beckett et al. 2000b;
296 Freer-Smith et al. 2004; Sæbø et al. 2012; Räsänen et al. 2013). Other characteristics of trees that
297 can enhance particulate matter accumulation include hairier leaves (Beckett et al. 2000a), rougher
298 leaves (Beckett et al. 2000c; Tiwary et al. 2009), more leaf wax (Sæbø et al. 2012), and trees with
299 greater structural complexity in their canopy, branches, and leaves (Beckett et al. 2000c; Freer-Smith
300 et al. 2004). Beckett et al. (2000c) demonstrated that larger trees collect more particulate matter than
301 trees of the same species that are younger and smaller, but that the younger and smaller trees can still
302 be effective in collecting particulate matter due to their higher foliage densities. The removal
303 efficiency of ultrafine particles in a wind tunnel by pine and juniper was determined to be higher for

304 smaller particle sizes, lower with increasing air velocity, and lower with decreased packing density
305 (Lin and Khlystov 2012). Mori et al. (2015) found that coniferous trees located next to a highway in
306 southwestern Norway intercepted PM_{10} and that the deposition efficiency was related to the tree
307 species, needle age, and the distance from the highway. Capture efficiencies and particle
308 accumulation for specific tree species can be found in Beckett et al. (2000a), Freer-Smith et al.
309 (2004), and Blanusa et al. (2015).

310

311 Herbaceous plant species can also capture particulate matter (Dzierżanowski et al. 2011; Speak et al.
312 2012; Weber et al. 2014). Analysis of leaves harvested from roadside herbaceous vegetation in Berlin
313 showed that species with the highest particulate matter accumulation rates were ones with hairy or
314 rough leaves and that leaves 15 cm or higher from the ground collected more particulate matter
315 (Weber et al. 2014). Herbs with smooth leaves and grasses were found to accumulate less particulate
316 matter than other plants with hairy leaves (Weber et al. 2014).

317

318 **Discussion: General Design Considerations for Green Streets**

319 Green street implementation often involves adjusting roadway design parameters in concert with
320 structural and landscape features that treat runoff. For example, road narrowing and removal of curb
321 and gutter are two staples of the green streets (City of Seattle 2010). The choice of which SCMs is
322 also key. Currently, the most common factors that influence the type of practice include: post-
323 construction road width and shape, vehicular loading (permeable pavement), capital cost, line of
324 sight, soil infiltration capacity, above and below-ground utilities, adjacent private buy-in, social
325 acceptance (gaged during initial stages of the project), maintenance capability of SCM owner,
326 influence on integrity of pavement sub-base and surface material vis-à-vis ponded water, and the
327 ability to meet other green street goals such as tree cover, aesthetics, etc.

328

329 However, green street design and SCM selection could additionally be based on air quality factors,
330 as illustrated in the graphical abstract. Vegetated SCMs that have the ability to trap particulate matter
331 and potentially improve air quality include: right-of-way bioswales, stormwater bump-outs,
332 bioretention cells, suspended pavement systems with street trees, and flow-through filter boxes.
333 These SCMs are often located close to road traffic emission sources (along roadways and in parking
334 lots) and can have diverse combinations of plant species. The close proximity of the vegetation to
335 the particulate matter emission sources maximizes the efficiency of interception and deposition; also,
336 the smaller plants, shrubs, and grasses in these SCMs do not significantly hinder air flow within the
337 street (Litschke and Kuttler 2008).

338

339 The strategic placement and design of green infrastructure is necessary to enhance particulate matter
340 capture and to prevent the possibility of green infrastructure inadvertently worsening air quality.
341 Vegetated green infrastructure systems can be employed in urban areas to potentially reduce
342 pedestrian and cyclist exposure to particulate matter, especially from vehicle traffic emissions.
343 Although trees within street canyons may worsen localized air quality, one must remember that trees,
344 vegetation, and forests in urban areas can significantly reduce regional air pollution (Nowak et al.
345 2006; McDonald et al. 2007; Tiwary et al. 2009). Characteristics that can affect pollutant
346 concentrations in street canyons includes the width to height ratio (W/H) of the street to the buildings,
347 wind direction, and tree positioning and arrangement (Gromke and Ruck 2007; Buccolieri et al. 2009,
348 2011; Wania et al. 2012). This review offers suggestions and advice for the placement, design, and
349 planting scheme of stormwater green streets when considering their air quality impacts.

350

351 *Considerations for the Placement of Green Streets*

352 Carefully selecting the location of a future green street based on air quality considerations can
353 enhance the ecosystem services, in regards to trapping air pollutants, provided by the vegetated
354 SCMs. Green streets with trees would ideally be placed in non-street canyons and in areas without
355 high traffic. However, this is not always possible in urban areas because of space constraints and
356 other goal-driven needs for trees (e.g., stormwater management, urban cooling, aesthetics). Under
357 these constraints, only specific street canyons are feasible for green streets implementation. Factors
358 that affect the performance of a green street with respect to air quality include the W/H ratio of the
359 street canyon, any prevailing winds, and the climatic region in which the green street is built
360 (Buccolieri et al. 2009, 2011; Gromke and Ruck 2012; Setälä et al. 2013). Table 3 provides design
361 guidance for green streets within street canyons.

362

363 Buccolieri et al. (2009) found that the W/H ratio of the street canyon and approaching wind velocity
364 were the most critical factors in regards to pollutant concentration, compared to tree stand density
365 and crown porosity. The researchers found that as W/H increases, the effect of trees on pollutant
366 concentration decreases no matter the tree morphology or arrangement (Buccolieri et al. 2009). For
367 street canyons with trees, a W/H = 1 can reduce flow by 62%, while in a wider street (W/H = 2) the
368 flow is reduced by 33% (Buccolieri et al. 2009). Large increases in pollutant concentrations occurred
369 within the street canyon (with trees) for all scenarios tested as compared to a tree-less street canyon
370 (Buccolieri et al. 2009). Jin et al. (2014) monitored PM_{2.5} concentrations within street canyons (tree-
371 free and with trees) in Shanghai, China. In tree-free street canyons, PM_{2.5} concentrations decreased

372 with increasing heights (Jin et al. 2014). However, in street canyons with trees, concentration
373 reduction was less pronounced or even increased with increasing tree height (Jin et al. 2014).
374 However, Vranckx et al. (2015) via modeling and wind tunnel validation showed the effect of trees
375 within street canyons on air quality might be less pronounced than that predicted by other studies;
376 annual average PM₁₀ concentrations increased by only 1.4% after the addition of street trees.

377

378 Buccolieri et al. (2011) determined that wind flow perpendicular to the street axis in a street canyon
379 with trees and a small W/H ratio has the most impact on pollutant concentrations, whereas for a street
380 canyon with trees and a larger W/H ratio the impact is greatest when the wind flow is oblique (45°)
381 to the street axis. Gromke and Ruck (2012) further found that an oblique wind direction had the
382 greatest impact on pollutant concentrations within the modeled street canyon with trees for both W/H
383 = 1 and W/H = 2. These studies highlight the need for designers and planners to consider both the
384 street canyon ratio and prevailing winds when considering the placement of green streets. The
385 research on street canyon ratios and prevailing winds suggests that the placement of the green streets
386 is the most important factor when considering air quality (ahead of planting schemes and tree
387 selection). Green streets with trees perhaps should not be placed in street canyon locations with
388 strong perpendicular or oblique prevailing winds. Furthermore, until additional research has been
389 performed placing green streets (with street trees) within street canyons with a W/H ratio ≤ 2 should
390 probably be avoided, if air quality is at all a concern. Green streets built within these street canyons
391 should employ SCMs that are designed without trees including permeable pavement, bioswales,
392 stormwater bump-outs, and types of bioretention cells.

393

394 One way city planners and designers can prioritize green street placement when air pollution is a
395 concern is to marry a green street canopy configuration with the local vehicle types and conditions
396 seen on that particular street. Neighborhood roads with high bicycle traffic and only one lane of
397 traffic may require addressing pollutant capture with tree canopies differently than a road trafficked
398 by larger commercial delivery trucks and/or high volumes of personal vehicles.

399

400 Finally, the climatic region a green street is built in will likely influence its air quality performance.
401 The role of vegetation in removing particulate matter from cities in subpolar climates may be less
402 significant than in other climates due to shorter in-leaf seasons and the percentage of deciduous tree
403 cover versus coniferous (Nowak et al. 2006; Setälä et al. 2013). Therefore, green streets built in
404 subpolar climates may not need to be designed around enhancing air quality through trapping

405 particulate matter; however, designers should be aware of green street characteristics that can
406 diminish air quality.

407

408 *Planting Schemes and Management*

409 **Street Canyon Considerations**

410 Although trees can be effective at reducing particulate matter levels in urban areas, dense tree cover
411 within street canyons should be avoided (Buccolieri et al. 2009, 2011; Wania et al. 2012; Vos et al.
412 2013; Abhijith et al., 2017). If there are trees within street canyons, Wania et al. (2012) recommends
413 careful management of the crowns, including pruning, to promote air flow. Small tree crowns and
414 trees with few leaves do not have much effect on pollutant concentrations; however, as tree crown
415 diameter is increased the upward flow and dispersion of air become limited, leading to higher
416 pollutant concentrations inside the street canyon (Gromke and Ruck 2007; Wania et al. 2012). It is
417 recommended that there be adequate space between the tree crowns and nearby walls (Gromke and
418 Ruck 2007) and the fewer trees that are planted leads to lower pollutant concentrations within the
419 street canyon (Vos et al. 2013). Gromke and Ruck (2007) demonstrated that tree spacing also plays
420 an important role in particulate matter concentrations and that close tree spacing within a street
421 canyon negatively affects localized pollution concentrations. They estimated that increasing the
422 spacing between trees from 15 m to 20 m decreased pollutant concentrations along one side of the
423 street canyon by 26% with standing traffic and 9% for two-way traffic (Gromke and Ruck 2007).
424 Tree height is also an important factor, with Gromke and Ruck (2007) recommending that tree height
425 shouldn't exceed the height of nearby buildings, due to changes in the level of entrained air in the
426 street canyon. Wind tunnel and modeling experiments of trees within street canyons directed
427 Buccolieri et al. (2009) to this recommendation: "A wider street canyon with two parallel aligned
428 rows of trees [on each side of the street] is the preferable configuration which should be taken into
429 account by urban planners rather than a narrow street canyon with only a single row of trees."

430

431 Including herbaceous vegetation in green street SCMs along with trees and shrubs can also help
432 improve removal rates of particulate matter (Weber et al. 2014). All herbaceous roadside vegetation
433 sampled in a study by Weber et al. (2014) was shown to assist in the trapping of particulate matter
434 and the results demonstrated that different species captured different sizes and types of particulate
435 matter – highlighting the benefit of using assorted species. For green streets within street canyons,
436 designers may consider limiting the number of trees in bioretention cells and suspended pavement
437 systems and focus on using SCMs with herbaceous vegetation (e.g., bioretention cells and
438 bioswales).

439

440 Finally, Vos et al. (2013) found that green barriers (impermeable screens with vegetation) may be
441 the only method of green infrastructure that can reliably reduce pedestrian exposure to particulate
442 matter within street canyons. The researchers found that the permeability of hedges allows air
443 pollutants to travel through them and into the sidewalk; however, Wania et al. (2012) speculated that
444 hedges may be able to capture particulate matter due to their proximity to vehicle emissions.
445 Although green barriers are not a SCM, they could be included in the green street design for aesthetics
446 and potential air quality improvements.

447

448 **Non-Street Canyon Considerations**

449 For green streets not located in street canyons or high-traffic areas, a planting scheme for a green
450 belt described by Freer-Smith et al. (2004) could be considered for trapping particulates. This
451 landscaping plan involves “low shrubs set in front of deciduous broadleaves and finally to position
452 evergreen conifers at the very back” (Freer-Smith et al. 2004). This is similar to a planting scheme
453 for a green belt described by Nguyen et al. (2015) who advocated for “one or two rows of shrubs,
454 followed by mixed evergreen (coniferous tree) and timber trees, and lastly with shrubs.” Design
455 information provided on herbaceous vegetation and green barriers for street canyons also applies to
456 green streets not located in street canyons or highly-trafficked areas.

457

458 *Tree Selection*

459 Proper tree selection in urban areas can optimize particulate matter capture. Yang et al. (2015) looked
460 at the performance of the 100 most frequently occurring trees in 328 cities throughout the world in
461 removing particulate matter, as well as taking into account negative impacts the trees may have on
462 air quality and their suitability for urban areas. Of the ten most common tree species in urban areas,
463 only three were ranked as above average for their ability to trap particulates: London plane (*Platanus*
464 *acerifolia*), silver maple (*Acer saccharinum*), and honey locust (*Gleditsia triacanthos*). Other
465 particulate-trapping broadleaf species on that list were the Red maple (*Acer rubrum*), silver linden
466 (*Tilia tomentosa*), and American elm (*Ulmus americana*). While conifer trees are not frequently
467 planted in urban areas, Yang et al. (2015) saw their use as an opportunity to promote the planting of
468 certain conifers in cities. Also, evergreen conifers are more effective during the out-of-leaf season
469 than deciduous trees (Beckett et al. 2000b). However, conifers can be less tolerant to air pollution
470 from traffic and salt from road deicing (Dzierżanowski et al. 2011; Burkhardt and Pariyar 2014).
471 Therefore, Beckett et al. (2000b) concluded that deciduous broadleaf species may be better for urban
472 planting despite their relatively lower particulate matter capture rates. Tiwary et al. (2016) developed

473 a performance index for green infrastructure vegetation selection based on seven factors, including
474 pollution flux potential. Small-to-medium size trees and evergreen shrubs were found to be more
475 desirable in urban street landscaping than larger trees (Tiwary et al. 2016) in regards to air quality.
476 This is at odds with current green infrastructure practices of planting large trees for their stormwater
477 benefits and creating SCMs that enhance tree growth (Smiley et al. 2006).

478

479 Trees in urban areas that should be avoided, especially along streets or by pavement, include (1) trees
480 without tolerance to air pollutants, heat, and drought (2) trees with highly allergenic pollen and (3)
481 invasive species (Yang et al. 2015). Street trees tend to have high stress levels and relatively high
482 mortality rates (Nowak et al. 2004). Pavement and soil compaction can limit tree root growth (Smiley
483 et al. 2006) and an increase in impervious cover reduces infiltration (Leopold 1973), decreasing the
484 amount of soil-water available. However, suspended pavement systems, which may include
485 permeable pavement, can be used to provide lightly compacted soil for tree growth. Suspended
486 pavement systems have been shown to improve tree growth, color, and root growth compared to
487 trees growing in compacted soils (Smiley et al. 2006). Suspended pavement systems also provide
488 stormwater management benefits including reduced peak runoff rates and improved water quality
489 (Page et al. 2015a). Suspended pavement design recommendations are made specifically for tree
490 health and based upon a volume of soil (e.g., Marritz 2013); however, they currently do not mandate
491 (or even lead to) a 20m tree spacing.

492

493 Proper management (e.g., watering, fertilizing, and pruning) is recommended to reduce mortality
494 rates and improve the ecosystem services provided by urban trees (Nowak et al. 2004; Jim and Chen
495 2008). Because trees within SCMs receive water and nutrients from runoff they treat (Passeport and
496 Hunt 2009) less management is needed for those trees (with the exception of pruning).

497

498 **Summary and Future Research Needs**

499 Strategic urban planning incorporating innovative systems and policies is necessary to reduce the
500 human health and environmental impacts of urbanization. Many municipalities implement green
501 infrastructure within the right-of-way transportation corridor as a means to comply with regulations
502 while also improving urban livability. Vegetated green infrastructure systems have the ability to
503 reduce particulate matter levels in urban areas (Beckett et al. 1998; Nowak et al. 2006), thus
504 improving the quality of life for urban citizens and increasing life expectancies (Samet et al. 2000;
505 Pope et al. 2009). Stormwater green streets can be designed to take advantage of the air quality
506 ecosystem services provided by street trees and vegetated SCMs including: bioswales, stormwater

507 bump-outs, bioretention cells, suspended pavement, and flow-through filter boxes. Care must be
508 taken when designing and implementing green streets in potential urban hot-spots of poor air quality
509 because street trees can limit the upward flow and dispersion of air and pollutants. These hot-spots
510 can include traffic intersections, busy roadsides, and street canyons (Goel and Kumar 2014). Factors
511 that affect the air quality within stormwater green streets include their placement, planting schemes,
512 and tree selection as detailed in the paper. Based upon the current research available, green street
513 placement (in regards to street canyon ratios and prevailing winds) appears to be the most important
514 factor of the three impacting air quality assuming the green street will have street trees. Therefore,
515 until further research is performed, perhaps limiting green streets containing street trees to a W/H
516 ratio > 2 should be considered. Additionally, perhaps green streets with trees should not be placed in
517 street canyon locations with strong perpendicular or oblique prevailing winds. Dense tree cover
518 should be avoided in green street canyons; tree height, spacing, crown diameter, and species can
519 affect particulate matter concentrations (Buccolieri et al. 2009; Wania et al. 2012; Vos et al. 2013).
520 Tree species should be carefully selected by green street designers to enhance particulate matter
521 capture, with more research needed on the capture efficiencies of trees commonly found in urban
522 areas. These issues highlight that careful planning and design of green streets in urban areas is
523 needed.

524

525 Further research is needed to determine the performance, design, and best placement of various
526 vegetated green infrastructure systems in regards to reducing particulate matter concentrations. The
527 negative impacts that street trees can have on air quality also need to be more clearly defined so that
528 systems can be placed where they will not increase exposure of the green street users to harmful
529 pollutants. The authors have provided design guidance for green streets and their air quality
530 considerations based on the current research available; however, there is a relative dearth of data on
531 the subject, limiting the formulation of more specific guidelines. This paper aims to promote further
532 research on the nexus of the urban stormwater management and air quality. This includes the
533 development of a decision-making process based upon quantitative data regarding green street
534 placement, planting schemes, and tree selection based on air quality. Specific research needs are
535 highlighted:

- 536 • The movement and air quality impacts of ultrafine particles (< 100 nm) and vegetation's ability
537 to act as a sink for ultrafine particles needs to be investigated.
- 538 • Tree selection in regards to PM trapping (to provide guidance on trees best suited for SCMs)
- 539 • The impact of temporarily trapped particulate matter on subsequent wash-off water quality
- 540 • Tree spacing (between each other, buildings, and the road)

- 541 • PM exposure in street canyons in regards to trees, W/H ratio, and other SCMs with vegetation
542 • Is there a safe W/H ratio for street tree addition?
543 • The creation of more specific green street design guidelines for considering air quality based
544 upon street characteristics, vehicular and pedestrian traffic levels, and climate.
545 Overall, SCM and green street design (size, height, species type), placement, and function
546 (particulate matter capture and air movement, nearby and downwind) must be better understood.
547

548 **Acknowledgements**

549 The authors thank the University Global Partnership Network (UPGN) of the University of Surrey
550 and NC State, along with the City of Fayetteville, North Carolina, for funding this research. The
551 authors would also like to thank Sheida Moin for creating the graphical abstract.

552 Tables/Figures

553

554 Table 1. Summary of Select Green Streets with Monitored or Modeled Stormwater Data Available in the United States.

Source	Location	Install phase (retrofit/new)	Year built	Length or area treated	Characteristics	Quantified Stormwater Benefits
Page et al.(2015b)	Wilmington, NC, USA	retrofit	2012	0.54 lane-km 0.53 ha	Two bioretention bump outs to pinch traffic, two permeable pavement parallel parking sections, one tree filtration box at watershed outlet.	28% decreased peak flow, 52% decrease in mean runoff depth; Runoff coefficient decreased from 0.38 to 0.18; Reductions in particle-bound pollutant loads; no change in dissolved pollutant concentrations
Horner et al. (2002)	Seattle, WA, USA	retrofit	2001	0.40 lane-km 0.93 ha	Reduced road width of residential road from 7.6 to 4.3 m, converted 18 m of pavement right of way to tree and shrub detention swales	93.2% of rainfall events detained completely (2001-2003 study); outflow reduced from 1.52 to 0.03 m ³ per mm of rainfall
Horner and Chapman (2007)	NW 110 th Street, Seattle, WA, USA	retrofit	2002-2003	7.4 ha	12 bioretention cells in a 274-meter cascade series along the road, separated by concrete weirs in a step-pool configuration.	79% of rain events did not discharge; completely retained 7.6 mm events and smaller; maximum estimated volume reduction is 74% during study; 85-90% total suspended solids reduction
D.C. DOT (2010)	Washington D.C., USA	retrofit	2012	2.4 lane-km 0.86 ha	2 bioretention cells in the right-of-way, 1 bio-swale, 12 stormwater planters, and permeable concrete sidewalk.	SWMM pre-construction model estimates 12% total volume reduction, fully captures 25.4 mm event and 1-year, 24-hour recurrence event

555

556

557

558

559

560 Table 2. Summary of Studies Addressing Urban Tree Particulate Capture.

Location	Scope	Type of PM	PM Removal per year
Chicago, USA ^a	Urban trees	PM ₁₀	212 t
Conterminous USA ^b	Urban trees	PM ₁₀	214,900 t
50 cities in conterminous USA ^b	Urban trees	PM ₁₀	3,570 t in Jacksonville, FL (highest) to 7 t in Bridgeport, CT (lowest)
Guangzhou, China ^c	Urban trees	TSP ^g	107 Mg
Midtown Toronto, Canada ^d	Urban trees and shrubs	PM ₁₀	8.3 Mg
10 cities in conterminous USA ^e	Urban trees	PM _{2.5}	64.5 t in Atlanta, GA (highest) to 4.7 t in Syracuse, NY (lowest)
Conterminous USA ^f	Urban trees	PM _{2.5}	27,000 t

561 ^aNowak, 1994, ^bNowak et al. 2006, ^cJim and Chen 2008, ^dCurrie and Bass 2008, ^eNowak et al. 2013, ^fNowak et al. 2014, ^gTotal suspended particles

562
563
564
565
566

Table 3. Design Guidance for Green Streets within Street Canyons.

Element	Recommendation	Citation	Relation to SCM Design & Maintenance
Street W/H Ratio	If W/H ratio ≤ 2 , avoid adding trees (until additional research performed).	Buccolieri et al. 2009; Jin et al. 2014	Tree inclusion within bioretention, tree trenches, and suspended pavement systems should be limited.
Tree Selection	Fewer trees are better. Dense tree cover should be avoided.	Buccolieri et al. 2009; Vos et al. 2013	Tree inclusion within bioretention, tree trenches, and suspended pavement systems should be limited.
Tree Spacing	Avoid close spacing between individual trees and between trees and nearby buildings.	Gromke and Ruck 2007	Select smaller trees and/or be attentive to tree pruning. Placement of suspended pavement systems may be spaced out beyond that normally recommended.
Tree Height	Tree height should not exceed the height of nearby buildings.	Gromke and Ruck 2007; Bassuk et al. 2003	Select smaller trees and/or be attentive to tree pruning. Example trees for North America that may be sufficient include: Eastern Redbud (<i>Cercis Canadensis</i>), Winter King Hawthorne (<i>Crataegus viridis</i>), Honey Locust (<i>Gleditsia triacanthos</i>)
Tree Crown Diameter	Avoid trees with large tree crown diameter.	Gromke and Ruck 2007; Wania et al. 2012	Plant trees with small crowns and/or be attentive to tree pruning.
Other Vegetation	Include a mix of herbaceous plants, grasses, and shrubs within SCMs. Green barriers may be effective at reducing pedestrian exposure.	Nguyen et al. 2015; Vos et al. 2013; Weber et al. 2014	Include variety of herbaceous vegetation in bioretention cells and bioswales to promote PM removal. Rows of shrubs may be helpful.
Prevailing Winds	Avoid placing green streets in locations with oblique or perpendicular prevailing winds.	Buccolieri et al. 2011; Gromke and Ruck 2012	n/a
Climatic Region	Focus on not worsening air quality, not on improving it in subpolar climates.	Nowak et al. 2006; Setälä et al. 2013	Green streets in subpolar climates may not need to be designed around enhancing air quality because role of vegetation less significant in PM removal.
Green Barriers	Include them in hot spots to shield pedestrians from particulates.	Vos et al. 2013	Green barriers are not considered an SCM, but some research on their (probably) modest stormwater pollutant attenuation is needed.

570
571
572
573
574
575
576
577
578
579
580
581
582
583
584
585
586
587
588
589
590
591
592
593
594
595
596
597
598
599
600
601
602
603
604
605
606
607
608
609
610
611
612
613
614
615
616
617
618
619

References

- Abhijith, K.V., Kumar, P., Gallagher, J., McNabola, A., Baldauf, R.W., Pilla, F., Broderick, B., Sabatino, S.D., Pulvirenti, B., 2017. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A Review. *Atmospheric Environment* 162, 71-86.
- Ahmad, K., Khare, M., and Chaudhry, K.K. 2005. Wind tunnel simulation studies on dispersion at urban street canyons and intersections—a review. *Journal of Wind Engineering and Industrial Aerodynamics*, 93, 697-717.
- Al-Dabbous, A.N. and Kumar, P. 2014. The influence of roadside vegetation barriers on airborne nanoparticles and pedestrians exposure under varying wind conditions. *Atmospheric Environment*, 90, 113-124.
- Asleson, B.C., Nestingen, R.S., Gulliver, J.S., Hozalski, R.M., and Nieber, J.L. 2009. Performance assessment of rain gardens. *Journal of the American Water Resources Association*, 45(4), 1019–1031.
- Baldauf, R., McPherson, G., Wheaton, L., Zhang, M., Cahill, T., Bailey, C., Hempill Fuller, C., Withycombe, E., and Titus, K. 2013. Integrating Vegetation and Green Infrastructure into Sustainable Transportation Planning. Transportation Research Board. *TR News*, 288, 14-18.
- Bassuk, N., Curtis, D.F., Marranca, B.Z., and Neal, B. 2003. Recommended Urban Trees: Site Assessment and Tree Selection for Stress Tolerance. Urban Horticulture Institute, Department of Horticulture, Cornell University, Ithaca, New York, USA.
- Bean, E.Z., Hunt, W.F., and Bidelspach, D.A. 2007. Evaluation of Four Permeable Pavement Sites in Eastern North Carolina for Runoff Reduction and Water Quality Impacts. *Journal of Irrigation and Drainage Engineering*, 133(6), 583–592.
- Beckett, K.P., Freer-Smith, P.H., and Taylor, G. 1998. Urban woodlands: their role in reducing the effects of particulate pollution. *Environmental Pollution*, 99, 347-360.
- Beckett, K.P., Freer-Smith, P.H., and Taylor, G. 2000a. Particulate pollution capture by urban trees: effect of species and windspeed. *Global Change Biology*, 6, 995-1003.
- Beckett, K.P., Freer Smith, P.H., and Taylor, G. 2000b. Effective tree species for local air quality management. *Journal of Arboriculture*, 26, 12-19.
- Beckett, K.P., Freer-Smith, P.H., and Taylor, G. 2000c. The capture of particulate pollution by trees at five contrasting urban sites. *Arboricultural Journal*, 24, 209-230.
- Blanusa, T., Fantozzi, F., Monaci, F., and Bargagli, R. 2015. Leaf trapping and retention of particles by holm oak and other common tree species in Mediterranean urban environments. *Urban Forestry & Urban Greening*, 14(4), 1095-1101.
- Brown, R. and Hunt, W.F. 2011. Underdrain configuration to enhance bioretention exfiltration to reduce pollutant loads. *Journal of Environmental Engineering*, 137(2), 1082-1091.

620 Brown, R., and Borst, M. 2015. Nutrient infiltrate concentrations from three permeable pavement
621 types. *Journal of Environmental Management*, 164, 74–85.
622

623 Buccolieri, R., Gromke, C., Di Sabatino, S., and Ruck, B. 2009. Aerodynamic effects of trees on
624 pollutant concentration in street canyons. *Science of the Total Environment*, 407, 5247-
625 5256.
626

627 Buccolieri, R., Salim, S.M., Leo, L.S., Di Sabatino, S., Chan, A., Ielpo, P., de Gennaro, G.,
628 and Gromke, C. 2011. Analysis of local scale tree–atmosphere interaction on pollutant
629 concentration in idealized street canyons and application to a real urban junction.
630 *Atmospheric Environment*, 45, 1702-1713.
631

632 Burkhardt, J. and Pariyar, S. 2014. Particulate pollutants are capable to ‘degrade’ epicuticular
633 waxes and to decrease the drought tolerance of Scots pine (*Pinus sylvestris* L.).
634 *Environmental Pollution*, 184, 659-667.
635

636 Charron, A. and Harrison, R.M. 2005. Fine (PM2.5) and Coarse (PM2.5-10) Particulate Matter
637 on a Heavily Trafficked London Highway: Sources and Processes. *Environmental Science
638 & Technology*, 39, 7768-7776.
639

640 City of Austin, Texas. 2015. *Green Streets: An Introduction*. Accessed via:
641 https://austintexas.gov/sites/default/files/files/Transportation/Complete_Streets/GreenStreetsWeb092115.pdf. Accessed: 22-Feb 2016.
642
643

644 City of Pomona, California. 2014. *City of Pomona Green Streets Policy*. Accessed via:
645 http://ci.pomona.ca.us/mm/pubwrks/pdf/Pomona_Green_Streets_Policy_Final.pdf.
646 Accessed 22-Feb 2016.
647

648 City of Philadelphia, Pennsylvania. 2014. City of Philadelphia Green Streets Design Manual.
649 *Philadelphia Water Department*. Accessed via:
650 http://www.phillywatersheds.org/what_were_doing/gsdm. Accessed: 23-Feb 2016.
651

652 Matsuno, H. and Chiu, S. 2010. SEA Street. *City of Seattle, Seattle Public Utilities*. Access via:
653 http://nacto.org/docs/usdg/stormwater_management_challenge_matsuno.pdf. Accessed:
654 Feb-23 2016.
655

656 Colvile, R.N., Hutchinson, E.J., Mindell, J.S., and Warren, R.F. 2001. The transport sector as a
657 source of air pollution. *Atmospheric Environment*, 35, 1537-1565.
658

659 Dargay, J., Gately, D., and Sommer, M. 2007. Vehicle Ownership and Income Growth,
660 Worldwide: 1960-2030. *The Energy Journal*, 28, 143-170.
661

662 Davis, A., Hunt, W., Traver, R., and Clar, M. 2009. Bioretention technology: Overview of current
663 practice and future needs. *Journal of Environmental Engineering*, 135(3), 109–117.
664

665 Dirks, K.N., Sharma, P., Salmond, J.A., and Costello, S.B. 2012. Personal Exposure to Air
666 Pollution for Various Modes of Transport in Auckland, New Zealand. *The Open
667 Atmospheric Science Journal*, 6, 84-92.
668

669 D.C. DOT. 2014. The District of Columbia’s Multimodal Long-Range Transportation Plan:

670 Sustainability and Livability Element. *District Department of Transportation, Policy,*
671 *Planning & Sustainability Administration*. Accessed via:
672 [http://www.wemovedc.org/resources/Final/Part%202_Plan_Elements/Sustainability_and_](http://www.wemovedc.org/resources/Final/Part%202_Plan_Elements/Sustainability_and_Livability.pdf)
673 [Livability.pdf](http://www.wemovedc.org/resources/Final/Part%202_Plan_Elements/Sustainability_and_Livability.pdf). Accessed: Feb-24 2016.
674
675 Dzierzanowski, K., Popek, R., Gawrońska, H., Sæbø, A., and Gawroński, S.W. 2011. Deposition of
676 particulate matter of different size fractions on leaf surfaces and in waxes of urban forest
677 species. *International Journal of Phytoremediation*, 13, 1037-1046.
678
679 Eisenberg, B., Lindow, K.C., and Smith, D.R., eds. 2015. Permeable Pavements. *American Society*
680 *of Civil Engineers*.
681
682 Fassman, E.A. and Blackbourn, S. 2010. Urban Runoff Mitigation by a Permeable Pavement
683 System over Impermeable Soils. *Journal of Hydrologic Engineering*, 15(6), 475-485.
684
685 Fletcher et al. 2015. SUDS, LID, BMPs, WSUD and more – The evolution and application of
686 terminology surrounding urban drainage. *Urban Water Journal* 12(7), 525-542.
687
688 Freer-Smith, P.H., Holloway, S., and Goodman, A. 1997. The uptake of particulates by an urban
689 woodland: site description and particulate composition. *Environmental Pollution*, 95, 27-
690 35.
691
692 Freer-Smith, P.H., El-Khatib, A.A., and Taylor, G. 2004. Capture of particulate pollution by trees:
693 a comparison of species typical of semi-arid areas (*Ficus nitida* and *Eucalyptus globulus*)
694 with European and North American species. *Water, Air, and Soil Pollution*, 155, 173-187.
695
696 Girling, C. and Kellett, R. 2005. *Skinny streets and green neighborhoods: Design for environment*
697 *and community*. Washington, DC: Island Press.
698
699 Goel, A. and Kumar, P. 2014. A review of fundamental drivers governing the emissions, dispersion
700 and exposure to vehicle-emitted nanoparticles at signalised traffic intersections.
701 *Atmospheric Environment*, 97, 316-331.
702
703 Gromke, C. and Ruck, B. 2007. Influence of trees on the dispersion of pollutants in an urban street
704 canyon—experimental investigation of the flow and concentration field. *Atmospheric*
705 *Environment*, 41, 3287-3302.
706
707 Gromke, C., Buccolieri, R., Di Sabatino, S., and Ruck, B. 2008. Dispersion study in a street canyon
708 with tree planting by means of wind tunnel and numerical investigations—evaluation of
709 CFD data with experimental data. *Atmospheric Environment*, 42, 8640-8650.
710
711 Gromke, C. and Ruck, B. 2009. On the impact of trees on dispersion processes of traffic emissions
712 in street canyons. *Boundary-Layer Meteorology*, 131, 19-34.
713
714 Gromke, C. and Ruck, B. 2012. Pollutant concentrations in street canyons of different aspect ratio
715 with avenues of trees for various wind directions. *Boundary-Layer Meteorology*, 144, 41-
716 64.
717
718 Gulliver, J. and Briggs, D.J. 2007. Journey-time exposure to particulate air pollution. *Atmospheric*
719 *Environment*, 41, 7195-7207.
720

721 Heal, M.R., Kumar, P., and Harrison, R.M. 2012. Particles, air quality, policy and health. *Chemical*
722 *Society Reviews*, 41, 6606-6630.
723

724 Hinds, W.C., 1999. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne*
725 *Particles*, second ed. Wiley, New York.
726

727 Hofman, J., Bartholomeus, H., Calders, K., Van Wittenberghe, S., Wuyts, K., and Samson, R.
728 2014. On the relation between tree crown morphology and particulate matter deposition on
729 urban tree leaves: A ground-based LiDAR approach. *Atmospheric Environment*, 99, 130-
730 139.
731

732 Horner, R.R., Lim, H., and Burges, S.J. 2002. Hydrologic monitoring of the Seattle ultra-urban
733 stormwater management projects. *Water Resources Series Technical Report No. 170*.
734 Department of Civil and Environmental Engineering, University of Washington, Seattle,
735 Washington, USA.
736

737 Horner, R.R., Lim, H., and Burges, S.J. 2004. Hydrologic monitoring of the Seattle ultra-urban
738 stormwater management projects: summary of the 2000-2003 water years. *Water*
739 *Resources Technical Report No. 181*. Department of Civil and Environmental Engineering,
740 University of Washington, Seattle, Washington, USA.
741

742 Horner, R.R. and Chapman, C. 2007. *NW 110th Street natural drainage system performance*
743 *monitoring*. Prepared for Seattle Public Utilities. Department of Civil and Environmental
744 Engineering, University of Washington, Seattle, Washington, USA.
745

746 Hunt, W.F., Davis, A.P., and Traver, R.G. 2012. Meeting Hydrologic and Water Quality Goals
747 through Targeted Bioretention Design. *Journal of Environmental Engineering*, 138(6), 698
748 -707.
749

750 Inkiläinen, E.N., McHale, M.R., Blank, G.B., James, A.L., and Nikinmaa, E. 2013. The role of
751 residential urban forest in regulating throughfall: a case study in Raleigh, North Carolina,
752 USA. *Landscape and Urban Planning*, 119, 91-103.
753

754 James, L.D. 1965. Using a digital computer to estimate the effects of urban development on flood
755 peaks. *Water Resources Research*, 1(2), 223-234.
756

757 Jeanjean, A.P., Hinchliffe, G., McMullan, W.A., Monks, P.S., and Leigh, R.J. 2015. A CFD study
758 on the effectiveness of trees to disperse road traffic emissions at a city scale. *Atmospheric*
759 *Environment*, 120, 1-14.
760

761 Jim, C.Y. and Chen, W.Y. 2008. Assessing the ecosystem service of air pollutant removal by urban
762 trees in Guangzhou (China). *Journal of Environmental Management*, 88, 665-676.
763

764 Jin, S., Guo, J., Wheeler, S., Kan, L., and Che, S. 2014. Evaluation of impacts of trees on PM 2.5
765 dispersion in urban streets. *Atmospheric Environment*, 99, 277-287.
766

767 Kumar, P., Khare, M., Harrison, R.M., Bloss, W.J., Lewis, A., Coe, H., and Morawska, L. 2015.
768 *New Directions: Air pollution challenges for developing megacities like Delhi*.
769 *Atmospheric Environment*, 122, 657-661.
770

771 Kumar, P., Andrade, M.F., Ynoue, R.Y., Fornaro, A., de Freitas, E.D., Martins, J.L.D.,
772 Albuquerque, T., Zhang, Y., and Morawska, L. 2016. New Directions: From
773 biofuels to wood stoves: the modern and ancient air quality challenges in the megacity of
774 São Paulo. *Atmospheric Environment*, 140, 364-369.
775
776 Leopold, L.B. 1968. *Hydrology for urban land planning – A guidebook on the hydrologic effects of*
777 *urban land use*. Circular 554, U.S. Geological Survey.
778
779 Leopold, L.B. 1973. River channel change with time: an example address as Retiring President of
780 The Geological Society of America, Minneapolis, Minnesota, November 1972. *Geological*
781 *Society of America Bulletin*, 84, 1845-1860.
782
783 Lin, M.Y. and Khlystov, A. 2012. Investigation of ultrafine particle deposition to vegetation
784 branches in a wind tunnel. *Aerosol Science and Technology*, 46(4), 465-472.
785
786 Lindeburg, M.R. 2014. *Civil Engineering Reference Manual for the P.E. Exam* (14th ed.).
787 Professional Publications, Inc., Belmont, CA. ISBN: 978-1-59126-453-8.
788
789 Litschke, T. and Kuttler, W. 2008. On the reduction of urban particle concentration by vegetation—a
790 review. *Meteorologische Zeitschrift*, 17, 229-240.
791
792 Lorenzini, G., Grassi, C., Nali, C., Petiti, A., Loppi, S., and Tognotti, L. 2006. Leaves of
793 *Pittosporum tobira* as indicators of airborne trace element and PM 10 distribution in central
794 Italy. *Atmospheric Environment*, 40(22), 4025-4036.
795
796 Lormand, J.R. 1988. *The effects of urban vegetation on stormwater runoff in an arid environment*.
797 Master's Thesis. School of Renewable Natural Resources, University of Arizona, Tucson,
798 AZ, USA.
799
800 Marritz, L. 2013. Our Recommended Soil Volume for Urban Trees. *DeepRoot – Green*
801 *Infrastructure for your Community*. Accessed via: [http://www.deeproot.com/blog/blog-](http://www.deeproot.com/blog/blog-entries/our-recommended-soil-volume-for-urban-trees)
802 [entries/our-recommended-soil-volume-for-urban-trees](http://www.deeproot.com/blog/blog-entries/our-recommended-soil-volume-for-urban-trees). Accessed: 22-March 2017.
803
804 Mayer, H. 1999. Air pollution in cities. *Atmospheric Environment*, 33, 4029-4037.
805
806 McDonald, A.G., Bealey, W.J., Fowler, D., Dragosits, U., Skiba, U., Smith, R.I., Donovan, R.G.,
807 Brett, H.E., Hewitt, C.N., and Nemitz, E. 2007. Quantifying the effect of urban tree
808 planting on concentrations and depositions of PM 10 in two UK conurbations. *Atmospheric*
809 *Environment*, 41, 8455-8467.
810
811 McPherson, G.E., Nowak, D.J., and Rowntree, R.A. 1994. *Chicago's urban forest ecosystem:*
812 *results of the Chicago Urban Forest Climate Project*. United States Department of
813 Agriculture – Forest Service.
814
815 Moore, T.L. and Hunt, W.F. 2012. Ecosystem service provision by stormwater wetlands and
816 ponds—A means for evaluation?. *Water Research*, 46(20), 6811-6823.
817
818 Mori, J., Hanslin, H.M., Burchi, G., and Sæbø, A. 2015. Particulate matter and element
819 accumulation on coniferous trees at different distances from a highway. *Urban Forestry &*
820 *Urban Greening*, 14(1), 170-177.
821

822 Napoli, M., Massetti, L., Brandani, G., Petralli, M., and Orlandini, S. 2016. Modeling tree shade
823 effect on urban ground surface temperature. *Journal of Environmental Quality*, 45(1), 146-
824 156.
825

826 Nguyen, T., Yu, X., Zhang, Z., Liu, M., and Liu, X. 2015. Relationship between types of urban
827 forest and PM 2.5 capture at three growth stages of leaves. *Journal of Environmental*
828 *Sciences*, 27, 33-41.
829

830 Nicholson, S.E. 1975. A pollution model for street-level air. *Atmospheric Environment*, 9(1), 19-
831 31.
832

833 Norton, B.A., Coutts, A.M., Livesley, S.J., Harris, R.J., Hunter, A.M., and Williams, N.S.G. 2015.
834 Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high
835 temperatures in urban landscapes. *Landscape and Urban Planning*, 134, 127–138.
836

837 Nowak, D.J. 1994. Air pollution removal by Chicago's urban forest. *Chicago's urban forest*
838 *ecosystem: Results of the Chicago urban forest climate project*, USDA Forest Service, 63-
839 81.
840

841 Nowak, D.J. 2002. The Effects of Urban Trees on Air Quality. *USDA Forest Service*. Northern
842 Research Station, Syracuse, New York.
843

844 Nowak, D.J., Kuroda, M., and Crane, D.E. 2004. Tree mortality rates and tree population
845 projections in Baltimore, Maryland, USA. *Urban Forestry & Urban Greening*, 2(3), 139-
846 147.
847

848 Nowak, D.J., Crane, D.E., and Stevens, J.C. 2006. Air pollution removal by urban trees and shrubs
849 in the United States. *Urban Forestry & Urban Greening*, 4(3), 115-123.
850

851 Nowak, D.J., Hirabayashi, S., Bodine, A., and Hoehn, R. 2013. Modeled PM 2.5 removal by trees
852 in ten US cities and associated health effects. *Environmental Pollution*, 178, 395-402.
853

854 Nowak, D.J., Hirabayashi, S., Bodine, A., and Greenfield, E. 2014. Tree and forest effects on air
855 quality and human health in the United States. *Environmental Pollution*, 193, 119-129.
856

857 Oke, T.R. 1988. Street design and urban canopy layer climate. *Energy and Buildings*, 11(1), 103-
858 113.
859

860 Page, J.L., Winston, R.J., and Hunt, W.F. 2015a. Soils beneath suspended pavements: An
861 opportunity for stormwater control and treatment. *Ecological Engineering*, 82, 40-48.
862

863 Page, J.L., Winston R.J., Mayes D.B., Perrin C., Hunt W.F. 2015b. Retrofitting with innovative
864 stormwater control measures: Hydrologic mitigation of impervious cover in the municipal
865 right-of-way. *Journal of Hydrology*, 527, 923–932.
866

867 Panis, L.I., De Geus, B., Vandenbulcke, G., Willems, H., Degraeuwe, B., Bleux, N., Mishra, V.,
868 Thomas, I., and Meeusen, R. 2010. Exposure to particulate matter in traffic: a comparison
869 of cyclists and car passengers. *Atmospheric Environment*, 44 (19), 2263-2270.
870

871 Passeport, E. and Hunt, W.F. 2009. Asphalt Parking Lot Runoff Nutrient Characterization for Eight
872 Sites in North Carolina, USA. *Journal of Hydrologic Engineering*, 14(4), 352-361.

873
874 Pope, C.A., Ezzati, M., and Dockery, D.W. 2009. Fine-particulate air pollution and life expectancy
875 in the United States. *New England Journal of Medicine*, 360, 376-386.
876
877 Pugh, T.A., MacKenzie, A.R., Whyatt, J.D., and Hewitt, C.N. 2012. Effectiveness of green
878 infrastructure for improvement of air quality in urban street canyons. *Environmental
879 Science & Technology*, 46(14), 7692-7699.
880
881 Räsänen, J.V., Holopainen, T., Joutsensaari, J., Ndam, C., Pasanen, P., Rinnan, Å., and
882 Kivimäenpää, M. 2013. Effects of species-specific leaf characteristics and reduced water
883 availability on fine particle capture efficiency of trees. *Environmental Pollution*, 183, 64-
884 70.
885
886 Sæbø, A., Popek, R., Nawrot, B., Hanslin, H.M., Gawronska, H., and Gawronski, S.W. 2012. Plant
887 species differences in particulate matter accumulation on leaf surfaces. *Science of the Total
888 Environment*, 427, 347- 354.
889
890 Samet, J.M., Dominici, F., Curriero, F.C., Coursac, I., and Zeger, S.L. 2000. Fine particulate air
891 pollution and mortality in 20 US cities, 1987–1994. *New England Journal of Medicine*,
892 343, 1742-1749.
893
894 Schaubroeck, T., Deckmyn, G., Neiryneck, J., Staelens, J., Adriaenssens, S., Dewulf, J., Muys, B.
895 and Verheyen, K. 2014. Multilayered modeling of particulate matter removal by a growing
896 forest over time, from plant surface deposition to washoff via rainfall. *Environmental
897 Science & Technology*, 48(18), 10785-10794.
898
899 Schueler, T.R., Fraley-McNeal L., and Capiella, K. 2009. Is impervious cover still important?
900 Review of recent research. *Journal of Hydrologic Engineering*, 14(4), 309-315
901
902 Shamma, T. November 2015. Atlanta is Home to Largest Permeable Pavers Project in US. WABE
903 – Atlanta’s NP Station. Accessed via: [http://news.wabe.org/post/atlanta-home-largest-
904 permeable-pavers-project-us?nopop=1](http://news.wabe.org/post/atlanta-home-largest-permeable-pavers-project-us?nopop=1). Accessed: 18-April 2017.
905
906 Shuster, W.D., Gehring, R., and Gerken, J. 2007. Prospects for enhanced groundwater recharge via
907 infiltration of urban storm water runoff: A case study. *Journal of Soil and Water
908 Conservation*, 62(3), 129–137.
909
910 Setälä, H., Viippola, V., Rantalainen, A.L., Pennanen, A., and Yli-Pelkonen, V. 2013. Does urban
911 vegetation mitigate air pollution in northern conditions?. *Environmental Pollution*, 183,
912 104-112.
913
914 Smiley, E.T., Calfee, L., Fraedrich, B.R., and Smiley, E.J. 2006. Comparison of structural and
915 noncompacted soils for trees surrounded by pavement. *Arboriculture and Urban Forestry*,
916 32(4), 164-169.
917
918 Solecki, W.D., C. Rosenzweig, L. Parshall, G. Pope, M. Clark, J. Cox, and M. Wiencke. 2005.
919 Mitigation of the heat island effect in urban New Jersey. *Environmental Hazards*, 6(1), 39–
920 49.
921

922 Speak, A.F., Rothwell, J.J., Lindley, S.J., and Smith, C.L. 2012. Urban particulate pollution
923 reduction by four species of green roof vegetation in a UK city. *Atmospheric Environment*,
924 61, 283-293.
925

926 Tilley, J.S. and Slonecker, E.T. 2006. Quantifying the components of impervious surfaces.
927 Prepared for the U.S. Department of Transportation, Federal Highway Administration in
928 collaboration with the U.S. EPA. No. 2007-1008.
929

930 Tiwary, A., Sinnett, D., Peachy, C., Chalabi, Z., Vardoulakis, S., Fletcher, T., Leonardi, G.,
931 Grundy, C., Azapagic, A., and Hutchings, T.R. 2009. An integrated tool to assess the role
932 of new planting in PM10 capture and the human health benefits: a case study in London.
933 *Environmental Pollution*, 157(10), 2645-2653.
934

935 Tiwary, A. and Kumar, P. 2014. Impact evaluation of green–grey infrastructure interaction on
936 built-space integrity: an emerging perspective to urban ecosystem service. *Science of the*
937 *Total Environment*, 487, 350-360.
938

939 Tiwary, A., Williams, I.D., Heidrich, O., Namdeo, A., Bandaru, V., and Calfapietra, C. 2016.
940 Development of multi-functional streetscape green infrastructure using a performance
941 index approach. *Environmental Pollution*, 208, 209-220.
942

943 United Nations Habitat (UN Habitat). 2013. *Streets as Public Spaces and Drivers of Urban*
944 *Prosperity*. United Nations Human Settlements Programme, Nairobi, Kenya.
945

946 United Nations (UN). 2015. *World Urbanization Prospects: The 2014 Revision*. Department of
947 Economic and Social Affairs, Population Division, United Nations, New York, New York.
948

949 U.S. EPA. 2007. *National water quality inventory: Report to Congress—2002 reporting cycle*.
950 Rep. No. EPA 841-R-07-001, United States Environmental Protection Agency, Office of
951 Water, Washington, D.C., U.S.A.
952

953 U.S. EPA. 2016. *Particulate Matter*. Accessed via: <https://www3.epa.gov/pm/>. Accessed: 27-May
954 2016.
955

956 Vos, P.E., Maiheu, B., Vankerkom, J., and Janssen, S. 2013. Improving local air quality in cities: to
957 tree or not to tree?. *Environmental Pollution*, 183, 113-122.
958

959 Vranckx, S., Vos, P., Maiheu, B., and Janssen, S. 2015. Impact of trees on pollutant dispersion in
960 street canyons: A numerical study of the annual average effects in Antwerp, Belgium.
961 *Science of the Total Environment*, 532, 474-483.
962

963 Wania, A., Bruse, M., Blond, N., and Weber, C. 2012. Analysing the influence of different street
964 vegetation on traffic-induced particle dispersion using microscale simulations. *Journal of*
965 *Environmental Management*, 94, 91-101.
966

967 Ward, B., MacMullan, E., and Reich, S. 2008. The Effect of Low Impact Development on Property
968 Values. *Proceedings of the Water Environment Federation, Sustainability*, 318 – 323.
969

970 Council for Watershed Health. 2010. Water augmentation study: Research, strategy, and
971 implementation report. *Los Angeles and San Gabriel Rivers Watershed Council*. Accessed

972 via: <http://www.usbr.gov/lc/socal/reports/LASGwtraugmentation/report.pdf>. Accessed:
973 22-March 2017.

974

975 Weber, F., Kowarik, I., and Säumel, I. 2014. Herbaceous plants as filters: Immobilization of
976 particulates along urban street corridors. *Environmental Pollution*, 186, 234-240.
977

978 World Health Organization (WHO). 2014. *Ambient (outdoor) air quality and health: fact sheet*.
979 Accessed via: <http://www.who.int/mediacentre/factsheets/fs313/en/>. Accessed: 27-May
980 2016.
981

982 World Health Organization (WHO). 2016. *WHO Global Urban Ambient Air Pollution Database*
983 *(update 2016)*. Accessed via:
984 http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/. Accessed 27-May
985 2016.
986

987 Xiao, Q., McPherson, E.G., Simpson, J.R., and Ustin, S.L. 1998. Rainfall interception by
988 Sacramento's urban forest. *Journal of Arboriculture*, 24, 235-244.
989

990 Yan, J., Lin, L., Zhou, W., Ma, K., and Pickett, S.T. 2016. A novel approach for quantifying
991 particulate matter distribution on leaf surface by combining SEM and object-based image
992 analysis. *Remote Sensing of Environment*, 173, 156-161.
993

994 Yang, J., Chang, Y., and Yan, P. 2015. Ranking the suitability of common urban tree species for
995 controlling PM 2.5 pollution. *Atmospheric Pollution Research*, 6(2), 267-277.