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Title: Development of multi-functional streetscape green infrastructure using a performance index approach

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Abstract (limit 150 words only)

This paper presents a performance evaluation framework for streetscape vegetation. A performance index (PI) is conceived using the following seven traits, specific to the street environments – Pollution Flux Potential (PFP), Carbon Sequestration Potential (CSP), Thermal Comfort Potential (TCP), Noise Attenuation Potential (NAP), Biomass Energy Potential (BEP), Environmental Stress Tolerance (EST) and Crown Projection Factor (CPF). Its application is demonstrated through a case study using fifteen street vegetation species from the UK, utilising a combination of direct field measurements and inventoried literature data. Our results indicate greater preference to small-to-medium size trees and evergreen shrubs over larger trees for streetscaping. The proposed PI approach can be potentially applied two-fold: one, for evaluation of the performance of the existing street vegetation, facilitating the prospects for further improving them through management strategies and better species selection; two, for planning new streetscapes and multi-functional biomass as part of extending the green urban infrastructure.

Keywords: *green infrastructure; multi-functional; pollution; performance index; streetscape*

Capsule abstract: A performance index is developed and applied to fifteen vegetation species indicating greater preference to medium size trees and evergreen shrubs for streetscaping.

Highlights:

- A performance evaluation framework for streetscape vegetation is presented.
- Seven traits, relevant to street vegetation, are included in a performance index (PI).
- The PI approach is applied to quantify and rank fifteen street vegetation species.
- Medium size trees and evergreen shrubs are found more favourable for streetscapes.
- The PI offers a metric for developing sustainable streetscape green infrastructure.

1 **1. Introduction**

2 Streets usually cover more than a quarter of a city and offer opportunities for increasing tree density in
3 the existing urban fabric. Urban proliferation, typically through scattered patterns of low-density
4 developments, or infill of urban space with medium and high density dwellings, provide further
5 potentials for boosting managed vegetation along streetscapes¹ comprising of roads, streets,
6 sidewalks, squares, bridleways, etc. (LAEC, 2007; Jim and Chen, 2008; Stovin et al., 2008; Ignatieva
7 et al., 2010; Dawe, 2011). Planting trees along streetscapes has been considered useful for improving
8 urban health and wellbeing, especially in densely populated inner-city built environments
9 characterised by space constraints and high pollution levels (Pauleit 2003; Roy et al., 2012;
10 Vlachokostas et al., 2014). Through adequate policy measures and design strategies, street trees hold
11 multifarious potentials for improving human comfort at modest costs, primarily through passive
12 cooling, pollution alleviation (air, water, noise) and flood risk aversion (Shashua-Bar et al., 2010a;
13 Armson et al., 2013a; Nowak et al., 2014; Gromke et al., 2015). Recent findings suggest public and
14 private benefits of street trees in terms of their positive contributions to neighbourhood development
15 and sustainability (Pandit et al., 2013; Salmond et al., 2013). Street vegetation already constitutes a
16 substantial portion of green space cover in such regions globally, with reported tree densities of up to
17 158 and 300 stands per km of street respectively in Melbourne, Australia and Guangzhou, China
18 (Kendal et al., 2011). In cities with heavy industrial or traffic activities, ‘green belts’ have been
19 integral part of streetscapes (along ring roads and arterial/ trunk routes), primarily introduced to
20 mitigate odour, noise and air pollution (Chaulya, 2004; Rao et al., 2004; Pathak et al., 2011).

21
22 Several local authorities have developed roadside vegetation management plans, inviting developers
23 and residents to participate in increasing street tree population alongside their long term preservation
24 (LAEC, 2007; Hawkesbury City Council, 2010; Hall et al., 2012; Heidrich et al., 2013). However,
25 streets and other paved sites offer complex stress environments and therefore the suitability of trees
26 for such sites requires higher priority to stress tolerance over their aesthetic and other functionalities.
27 A review of Scandinavian tree species reported the existing information to be either piecemeal (and
28 very general, lacking local perspective) or too specific (and contradictory) to meet the requirements of
29 urban tree planners (Sjöman, H., & Nielsen, 2010). Traditionally, the resilience of an urban tree
30 population has been largely dependent on species selection to withstand pest infestations, i.e. natural
31 selection (Raupp et al., 2006; Bassuk et al., 2009). Common considerations guiding the selection of
32 species encompass, but are not limited to, their representativeness of native vegetation,
33 decorativeness, salt tolerance, ability to uptake soil contaminants, and growth performance (Churkina
34 et al., 2015). However, cities globally have witnessed habitat fragmentation and increased non-native
35 diversity of streetscape vegetation as a result of newly introduced species. This has been further

¹ Streetscapes are defined as planted specimens growing along the verge of streets (Barber et al., 2013).

36 aggravated during recent drive to increase urban green cover through fast-track programs to plant
37 millions of trees via national and/or international campaigns (Young, 2011; Zhao et al., 2013; Plant
38 the Planet, 2014). Such initiatives for creating ‘naturopolises’ are likely to succumb to environmental
39 stresses from the drastic differences between urban and natural systems unless due consideration is
40 given to developing resilient tree infrastructure using the scientific evidence on interactions between
41 plants and urban ambient conditions (Churkina et al., 2015). Street trees in particular are exposed to a
42 relatively high stress level, including high pollutant concentrations (Harris and Manning, 2010;
43 Demuzere et al., 2014); damage from wind gusts, de-icing salt, high/low ambient temperatures; harsh
44 growing conditions, including restricted rooting space owing to low quality growing substrate and soil
45 compaction (Gill et al., 2008; Armson et al., 2013a), restricted space for crown development (Sæbø et
46 al., 2005); and, insufficient access to water and oxygen, which are only likely to get worse with the
47 projected adverse future climate (Roloff et al., 2009). Increased urbanisation would further influence
48 the pollution dynamics and the alteration of the structure and function of the natural ecosystems
49 (Williams et al., 2009). This will evidently influence future tree assemblages along streets, which in
50 most cases is already dominated by just a few species. The European tree survey has shown that only
51 three to five genera, including *Platanus*, *Assculus*, *Acer*, *Tilia*, account for 50% to 70% of all street trees
52 planted (Pauleit 2003). Spain has only five genera representing 56% of all the trees planted in paved areas
53 (Sæbø et al., 2005); England, UK, has only six species accounting for 37% of all trees and shrubs
54 planted within cities, including Leyland cypress (\times *Cupressocyparis Leylandii*), hawthorn (*Crataegus*
55 *spp.*), sycamore (*Acer pseudoplatanus*), silver birch (*Betula pendula*), common ash (*Fraxinus*
56 *excelsior*), and privet (*Ligustrum spp.*) (Britt and Johnston 2008); the London Plane tree (*Platanus*
57 *acerifolia*) is among the most numerous large street and park trees planted in Greater London (UK)
58 (Davies et al., 2011).

59
60 A considerable amount of research efforts have gone into assessing the effects of air pollution on
61 roadside vegetation (Lau, 2001; Truscott et al., 2005; Wagh et al., 2006; Bignal et al., 2008) and
62 conversely on their role in mitigating air pollution (Yang, 2005; Nowak et al., 2006; McDonald et al.,
63 2007; Tiwary et al., 2009). Evaluation of the net effect of increased vegetation on the urban air quality
64 in the local-to-neighbourhood scale street environment has been a central theme of recent research
65 studies (Salmond et al., 2013; Gromke and Blocken, 2015). Increased traffic-generated N-emissions
66 have been associated with accelerated growth of some ‘lower plant’ species (e.g. bryophytes) along
67 streets, mainly owing to fertilisation effects of the scavenged NO_x, HNO₂ and/or NH₃ emissions on
68 their surfaces (Bignal et al., 2008). Certain tree species have been earmarked for plantations along the
69 roads as bio-monitors for vehicle emissions (Moreno et al., 2003; Hofman and Samson, 2014).
70 However, despite some generalised modelling studies, there is still much to be learned about the
71 characteristics and ecophysiology of different types of urban vegetation and their interaction with the
72 street environment (Calfapietra et al., 2015). This indicates an urgent need to improve our

73 understanding of the environmental responses of the vegetation species used before decisions are
74 made about streetscape species selection. Street tree good practice guides have been developed -
75 outlining the design criteria for street plantations, choice of suitable tree species and maintenance
76 requirements - with increasing emphasis on planting smaller tree species as street trees because they
77 fit better into narrow pavements and are easier to manage (Pauleit, 2003; Britt and Johnston 2008;
78 Armson et al., 2013b; Forest Research, 2014). A generalised prescription for suitable streetscape
79 vegetation species and genotypes include – tree life span; required growth space and adaptability to
80 the local environment; tree functionality (pollution/noise attenuation, cooling, flood risk aversion,
81 storm water reduction, etc.); cost of propagation, establishment and management; aesthetics; stress
82 and drought tolerance; potential allergenicity of species (Sæbø et al., 2005; Vlachokostas et al., 2014).

83

84 The scope of this study is to evaluate the inherent traits of high-performing streetscape vegetation,
85 deemed important for sustainable and widespread climate change mitigation as well as adaptation. It
86 is motivated by the emerging trends of adaptation strategies based on urban greening, maximising the
87 potentials for multiple benefits while avoiding the conflicting influences on meeting the objectives
88 (CLG, 2007). The development of a Performance Index (PI) framework is meant to facilitate the
89 decision-support of planners/practitioners by providing a repeatable metric for comparative
90 evaluations on the multitude of streetscaping prospects, such as planting a line of seasonal woody tree
91 biomass vs. perennial shrubs, or developing a vegetation mix, combining sparse line of trees with an
92 understory etc. The first part of this paper describes the methodological framework in developing the
93 performance index. The application of this methodology is demonstrated through a case study in the
94 second part of the paper. This is followed by a discussion on the relevance of such an approach, as
95 well as its limitations to conducting an all-inclusive evaluation of streetscape vegetation.

96

97 **2. Development of performance index**

98 Understanding and improving the environmental performance of street/roadside vegetation
99 comprehensively (trees, shrubs, forbs etc.) has motivated the development of index-based
100 frameworks. Several researchers have expended efforts towards developing performance indices for
101 specific application of urban trees – for example, towards greenbelt development for pollution
102 alleviation (Prajapati and Tripathi, 2008); for reducing of traffic-generated noise (Pathak et al., 2011);
103 for more comprehensive evaluation of their ecosystem services and goods from urban forests (Dobbs
104 et al., 2011; Kenney et al., 2011), etc. A recent study developed a decision-making scheme for
105 benchmarking/prioritising tree species in urban environments using a framework which combines two
106 multi-criteria methods to provide an optimal ranking. The set of multiple criteria include tree life
107 span, required growth space, planting capability in built environment, aesthetics, tolerance, pollution

108 attenuation, adaptation to local climate, crown density, cost, and potential allergenicity of species
109 (Vlachokostas et al., 2014). However, their study does not appear to address the issues pertaining to
110 street environment and has not considered biogenic emissions (BVOCs) from vegetation *per se*.

111 The performance index (PI) is conceived in this study as a combination of the following seven
112 performance traits for streetscaping vegetation – 1. Pollution Flux Potential (PFP) i.e. influence on
113 local-to-regional atmospheric pollutants, comprising of both uptake and release; 2. Carbon
114 Sequestration Potential (CSP) i.e. increased cycling of biogenic carbon; 3. Thermal Comfort Potential
115 (TCP) i.e. evapo-transpirative cooling; 4. Noise Attenuation Potential (NAP) i.e. abatement of traffic-
116 generated noise; 5. Biomass Energy Potential (BEP) i.e. renewable resource for bioenergy; 6.
117 Environmental Stress Tolerance (EST) i.e. resistance to toxic ambient urban pollutants and water
118 stresses; and 7. Crown Projection Factor (CPF) i.e. competition for space in the street environment.
119 The first five essentially depict the multi-functionality of street vegetation, the sixth its resilience and
120 the seventh is a dimensional trait. The latter two have been considered as overriding factors,
121 establishing the fitness for purpose of the species exclusively for street environments. Although
122 developing an all-inclusive performance index is deemed impractical, the above traits have been
123 considered essential towards developing resilient and multi-functional street plantations. A gradation
124 pattern is applied to substitute the finite estimates (values rounded off to one decimal place) with
125 increasing number of + or – , to acquire the overall PI of a species. This facilitates in harmonising the
126 disparate values using common metrics for comparison in terms of the equivalent PI score in the
127 decision matrix (see **Appendix A, Tables A.1 and A.2**). The following sections provide an overview
128 of the framework developed and its implementation to a case study.

129

130 *2.1 Pollution flux potential*

131 The pollution flux potential (PFP) accounts for the interactions of the foliage with the street
132 environment - for both the dry deposition and release of air pollutants. Urban vegetation have been
133 found to be effective filters in scavenging gaseous and particulate air pollution (Tiwary et al., 2009;
134 Sjöman and Nielsen, 2010; Buccolieri et al., 2011), with recent evaluations on the costs associated to
135 avoided health impacts (Nowak et al., 2014). During dry deposition, pollutants adhere to the surface
136 of plants where they may subsequently become re-suspended in the atmosphere, washed off by
137 rainfall or absorbed into the plant (Getter & Rowe, 2006; Currie & Bass, 2008; Jim & Chen, 2008;
138 Setälä et al., 2013). During gas transfer, gaseous pollutants are removed from the air by entering
139 plants through leaf stomata and reacting with compounds within the plant, a process which may result
140 in damage to the plant itself (Clark et al., 2008; Currie & Bass, 2008; Jim & Chen, 2008). The
141 effectiveness of vegetation in performing these functions is affected by factors such as plant species,
142 leaf area index and atmospheric conditions (Jim & Chen, 2009). Time of day and subsequently levels

143 of incoming solar radiation also significantly affect rates of plant gas exchange (Clark et al., 2008;
144 Kwak & Baik, 2014).

145 Nearly all plants emit pollens and biogenic volatile organic compounds (BVOC), the latter during
146 reproduction, growth, and defense. The BVOCs are emitted by leaves, flowers, and fruits of plants
147 and these compounds can exacerbate photochemical pollution (Calfapietra et al., 2013). A graphical
148 overview of BVOC emissions rates (in micrograms of isoprene or monoterpenes per gram of leaf
149 mass per hour) for a list of popular urban plants species is presented in Churkina et al. (2015); a more
150 detailed compilation of BVOC emissions from a wide range of vegetation species can be found in
151 Guenther (2013). The PFP of a species has been formulated using the available information on leaf-
152 level processes, as a net effect of annual pollutant deposition (P_{dep}) and emission (P_{emit}) weighted by
153 its seasonal leaf cover profile (Eq. [1]). The latter is parameterised as a coupled function of the leaf
154 cover during full foliation (expressed as leaf area index, LAI) and its annual profile (expressed as
155 intra-annual foliage factor, IAL i.e. the ratio of the number of months with foliage cover to the total
156 number of months in a year). This is aimed to account for the physiological differences attributed to
157 seasonal variations for deciduous and coniferous stands, providing a representative PFP.

$$158 \quad PFP = \left(1 - \frac{P_{emit}}{P_{dep}}\right) \times LAI \times IAL \quad [1]$$

159 Both P_{dep} and P_{emit} (expressed as kg yr^{-1}) can be either literature-derived (based on leaf-level activity
160 values of pollutant depositions and emissions) or directly acquired from field campaigns. P_{dep} includes
161 dry deposition of the following five air pollutants - ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide
162 (NO_2), carbon monoxide (CO), and particulate matter less than $10\mu\text{m}$ (PM_{10}). P_{emit} includes
163 emissions of isoprene, monoterpenes and other BVOCs (USDA, 2008). The quantification of pollen
164 emissions has not been included as part of P_{emit} owing to their narrow window of influence on an
165 annual basis.

166
167

168 2.2 Carbon sequestration potential

169 Vegetation sequester atmospheric carbon in the form of biomass and their sequestration potentials
170 vary widely between species depending on their phenology and growth characteristics (Davies et al.,
171 2011). Recent evaluations of carbon storage and sequestration by urban trees have been reported
172 (Escobedo et al., 2010; Zhao et al., 2010; Foster et al., 2011; Nowak et al., 2013). It is worth noting
173 that urban forests are estimated to store approximately 50% less carbon than natural forests – possibly
174 due to the younger age of trees in urban areas (Nowak & Crane, 2002; McPherson, 2010; Zhao et al.,
175 2010). However, a study by Nowak & Crane (2002) found rates of carbon sequestration decrease as a

176 tree matures so young trees in urban areas could be considered beneficial. The carbon sequestration
177 potential (CSP) takes into account the capacity of the entire plant to store carbon within woody, long-
178 lasting tissues considering that fine roots and litter have a relatively fast turnover. The carbon
179 sequestered in the soil has been omitted from these estimates owing to inadequate information to date
180 about the carbon fluxes in urban soils for a diverse range of street tree plantations and their
181 disturbances during road works, soil amendments, etc. Various approaches have been adopted to
182 determine the CSP of tree species, one of which is empirical equations, similar to the one shown in
183 (Eq. [2], expressed as kg yr^{-1}), based on field scale studies in terms of the total biomass carbon
184 content (Northup et al., 2005).

$$185 \quad CSP = AGB \times TBCF \times C \quad [2]$$

186 Where *AGB* is Above Ground Biomass (kg yr^{-1}), *TBCF* is total biomass conversion factor, and *C* is
187 carbon content of dry mass ($\text{kg C kg dry mass}^{-1}$) (0.5). We used empirical biomass equations (see
188 **Appendix B**) to estimate above ground biomass (AGB) and subsequently below ground biomass is
189 added to it to determine total biomass using a TBCF value of 1.28 (Aguaron and McPherson, 2012).

190

191

192 *2.3 Thermal Comfort Potential*

193 Street trees have been found effective in mitigating the effects of heat and drought at highly sealed
194 urban sites, can have a substantial cooling effect on the urban air temperature (Leuzinger et al., 2010;
195 Gillner et al., 2015), and have been reported to reduce cooling energy demand by 20% (Akbari et al.
196 (2001). Microclimate modelling of the cooling effect of street trees in their immediate vicinity show
197 strong dependence on three parameters - the built form geometry (building height and street width),
198 the canopy coverage level and planting density – with negligible influence of other species
199 characteristics, such as leaf size and other plant physiological parameters (Shashua-Bar et al., 2010a).
200 It is noteworthy, for any tree coverage level the cooling effect of street trees strongly vary with
201 available open space - deeper canyons (i.e. building height > street width) tend to reduce the tree
202 cooling effect, requiring trees with fastigiated crowns planted in those sites, mainly for shading and
203 thermal comfort in the noon hours; shallow canyons (i.e. street width > building height) on the other
204 hand enhance the cooling effect, requiring plantation of broad-leaf trees in minimum planting
205 intervals. Further, more drought-tolerant and slow-growing trees have been found to reduce radiation
206 less than faster-growing species, hence providing less evapo-transpirational cooling owing to their
207 less dense canopies (Armson et al., 2013b). Typically on a warm sunny day passive cooling offered
208 by a street tree (quantified as reduction in surface temperature and thermal loads) has been reported to
209 bear strong positive correlation with its canopy projection area and LAI (Armson et al., 2013b; Gillner

210 et al., 2015). These two tree characteristics have been used to parameterise its indicative Thermal
211 Comfort Potential (TCP) as shown in **Eq. [3]**

$$212 \quad TCP \sim CanopyArea \times LAI \quad [3]$$

213

214

215 *2.4 Noise Attenuation Potential*

216 Roadside vegetation belts have been found effective in traffic noise attenuation closer to the roads up
217 to 5-10 dB compared to bare grass in previous studies (Huddart, 1990; Fang and Ling, 2005; Pathak et
218 al., 2011). Typical traffic noise ranges between 1000 to 2000 Hz, which is considered to lie within an
219 ‘acoustic window’ between the low and high frequency noise, where high potential attenuation rates
220 from vegetation are not found effective, however, vegetation surfaces have been reported to make
221 traffic noise less annoying by filtering mainly high frequencies (Huddart, 1990; Pathak et al., 2011).
222 Dense canopies, typically with interlocking evergreen vegetation, show higher attenuation potential
223 than rarefied canopies, with studies recommending an optimal compromise between aesthetic and
224 acoustic performance by using a mixed stand with dense planting of broadleaved evergreens (e.g.
225 spruce) along with deciduous shrubs and conifers (Huddart, 1990; Ozer et al., 2007; Maleki et al.,
226 2010). Conventionally, the noise attenuation factor is expressed as the ratio of the mass flux reaching
227 a particular distance in absence of vegetation to the mass flux reaching the same distance in the
228 presence of vegetation (Pathak et al., 2011). An estimate of the indicative trend for Noise Attenuation
229 Potential (NAP) is obtained in terms of the available stand characteristics as follows (**Eq. [4]**).

$$230 \quad NAP \sim \frac{Avg.LeafBiomass}{(CanopyArea \times Height)} \times IAL \quad [4]$$

231

232

233 *2.5 Biomass Energy Potential*

234 Woody vegetation has been identified an important renewable resource for bioenergy, alleviating the
235 growing demand for cropped biofuels (de Richter et al., 2009). The bio energy potential (BEP)
236 evaluates the end-of-life use of the biomass – mainly the woody stock from chips, bark and pruning.
237 Recovery of bioenergy, mainly as heat from the combustion of the managed pruning/coppicing of the
238 street vegetation, is obtained from its heating value on a dry basis (BISYPLAN, 2012).
239 Conventionally, this is expressed in terms of either the Higher Heating Value (HHV) or the Lower
240 Heating Value (LHV) (both expressed as MJ kg⁻¹). The HHV on a dry basis is related to the typical
241 stoichiometric chemical composition of the biomass (**Eq. [5]**) following Sagani et al. (2014):

$$242 \quad HHV = 0.341 * C + 1.322 * H - 0.12 * (O + N) + 0.0686 * S - 0.0153 * Ash \quad [5]$$

243

244 Where, C , H , O , N , S and Ash denote the corresponding carbon, hydrogen, oxygen, nitrogen, sulfur
245 and ash content, in %w/w of the bio-fuel. However, since HHV reflects the total amount of heat
246 energy that is available in the fuel, including the energy contained in the water vapour of the exhaust
247 gases, LHV is considered more appropriate representation of the BEP (BISYPLAN, 2012), evaluated
248 as a function of HHV (Sagani et al., 2014). This has been weighted by the annual aboveground
249 biomass (AGB) of a stand (kg yr^{-1} , estimated in Section 2.2) to obtain its gross BEP (Eq. [6],
250 expressed as MJ yr^{-1}):

$$251 \quad BEP = LHV \times AGB = \left(HHV - \left(\frac{2.444 * 8.936 * H_{dry}}{100} \right) \times AGB \right) \quad [6]$$

252 In this expression, 2.444 (MJ kg^{-1}) refers to the latent heat of vaporisation of water at 25° C, whilst
253 8.936 (kg) refers to the quantity of water formed by burning 1 kg of hydrogen. H_{dry} (MJ kg^{-1}) denotes
254 the hydrogen content of the fuel.

255

256

257 2.6 Environmental Stress Tolerance

258 Environmental Stress Tolerance (EST) depicts the resilience of the street vegetation from water stress
259 and pollution damage. Unlike naturally forested or parkland areas, street trees are specifically
260 subjected to excessive environmental stresses induced by traffic-generated air and water pollution
261 (Bignal et al., 2008; Churkina et al., 2015), the latter exacerbated from water stress in
262 disturbed/compacted soils typically used in streetscapes (Quigley, 2004). Acute water stress in plants
263 leads to reduction in the leaf chlorophyll content from production of reactive oxygen species (ROS) in
264 the chloroplast (Pathak et al., 2011). On the other hand, such stresses lead to increase in ascorbic acid
265 content as a defensive response in order to protect thylakoid membranes of leaves from oxidative
266 damage under the influence of increased ROS (Tambussi et al., 2000). Also, plants with high leaf pH
267 show greater tolerance against air pollution (Prajapati and Tripathi, 2008). Using these criteria the
268 EST can be evaluated on the basis of species-specific analyses of four biochemical parameters (Eq.
269 [7]).

$$270 \quad EST = \frac{(A * (T + P)) + R}{10} \quad [7]$$

271 Where A and T are ascorbic acid the total chlorophyll content of leaf samples respectively (both
272 obtained as mg g^{-1} of fresh weight), P is the leaf extract pH and R is its relative water content (%).

273

274

275 *2.7 Crown Projection Factor*

276 The Crown Projection Factor (CPF) has been considered an important trait in characterising
277 streetscape vegetation. This is a measure of the lateral spread of a species at maturity, commonly
278 expressed in terms of the canopy projection area in the arboriculture literature (Shimano, 1997). It is
279 noteworthy that same tree species can potentially have different performance results for the majority
280 of the earmarked traits along roadside vs. open parklands. Recent studies have reported large street
281 trees as - obstacles to airflow, hampering the mixing of pollutants in poorly ventilated areas close to
282 streets owing to reduced air exchange with the above-roof ambient environment (Gromke et al., 2009;
283 Wania et al., 2012; Vos et al., 2013); damaging the road fabric owing to their deep rooting (Randrup
284 et al., 2001). While on one hand, fastigate (narrow) crowns are recommended as more effective in
285 trapping the traffic pollutants (Darcy and Forrest 2010; Farahani et al. 2012), planting density and
286 canopy coverage levels has been considered an important factor in noise reduction (Huddart, 1990;
287 Pathak et al., 2011) and evapo-transpirational passive cooling (Shashus-Bar et al., 2010; Armson et
288 al., 2013b) in urban streets. There is increasing emphasis on planting smaller tree species as street
289 trees because they fit better into narrow pavements and are easier to manage (Britt and Johnston
290 2008). CPF has been inversely associated with fitness for street plantation and given overriding
291 weightings (**Table A.1**) in the evaluation of PI, typically relevant for the narrow streets/roads in
292 western European countries. This is meant to overcome the negative feedbacks to both the air and the
293 soil environments in the street, potentially avoiding the competition between the road space and the
294 kerbside vegetation. The CPF of a species (expressed as m²) is directly proportional to its diameter at
295 breast height (DBH) (typically for DBH < 100 cm; Shimano, 1997) and approximated as a coupled
296 function of *DBH* and the stand height, *H* (in meters each) (**Eq. [8]**).

$$297 \quad CPF = DBH \times H \quad [8]$$

298

299

300 **3. Case study**

301 *3.1 Site description and species selection*

302 The case study site was located on an area spanning 250m×200m adjacent to a busy road network,
303 connecting the suburbs to Newcastle-upon-Tyne city center, UK (54.979°N, 1.6111°W). An initial
304 visual assessment of species abundance, proximity to the road and suitability for assessment was
305 carried out to draw a shortlist of fifteen species, comprising of a mix of deciduous and evergreen trees
306 and shrubs (**Table 1**). Inclusion of shrubs and forbs has been particularly recommended in the
307 literature for a better understanding of the full suite of multi-functionality of the urban ecosystems
308 (Dobbs et al., 2011). It is noteworthy that the life span for the majority of the street trees is much
309 shorter than their biological potentials owing to harsh growing conditions in urban paved sites (for
310 example, the average life expectancy of street trees is estimated to be currently around 60 years for

311 Berlin, but can be as low as 20 years. Monitoring of trees in inner city Liverpool showed that nearly
312 30% died within five years of planting (Pauleit, 2003).

313 <place Table 1 somewhere here>

314

315

316 3.2 Data collection and analysis

317 All sampling was performed within 100 m of the verge of the main road since literature evidence
318 suggests strongest effects of traffic-generated pollutants in the first 50-100 m from road (Bignal et al.,
319 2008), with particulates decreasing in concentration more rapidly than gaseous constituents, and gases
320 with a high deposition velocity (such as HNO₂ and NH₃) decreasing more rapidly than those with a
321 lower deposition velocity (such as NO and NO₂) (Truscott et al., 2005). The earmarked traits for the
322 vegetation species were evaluated using a combination of experiments and literature survey for
323 acquiring the underlying datasets, as described below and summarised in **Table 2**.

324

325 3.2.1 Pollution Flux Potential

326 Inventory data from the i-Tree model (Nowak et al., 2006; USDA, 2008) have been used for both P_{dep}
327 and P_{emit} . This approach overcame the complexities in simultaneous, long-term measurement of
328 pollutant fluxes in busy urban street environments. For P_{dep} validation, nitrogen concentrations were
329 used as proxy given the site was close to heavy traffic activity. The nitrogen analysis was performed
330 following a method adapted from Bignal et al. (2008). For P_{emit} validation, isoprene concentrations
331 have been used as proxy, estimated for UK-specific inventoried leaf-level emissions data following
332 Guenther (2013).

333 3.2.2 Carbon Sequestration Potential

334 Within the study area, all trees have been inventoried and structural data measured, i.e. diameter at
335 breast height, height, crown depth, crown wideness, health status of the plant, and crown exposure to
336 light. For each species, its CSP has been considered directly proportional to its *AGB* (using **Eq. [2]**),
337 the latter expressed as a function of its stand height and the *DBH* using empirical biomass equation
338 (based on **Table 1**). The empirical biomass equations used in our estimates are acquired from the
339 documented literature, representative of the European growing conditions (see **Appendix Table B.1**)
340 for average plant age up to 250 years. Apparently, all the vegetation included in this study were of
341 lower age than this threshold (maximum of 234 for beech as shown in **Table 1**), therefore we consider
342 the equations applicable to the estimation. Species lacking reported information have been
343 approximated to their closest match; for example, both *Berberies* and *Larustinus* have been
344 generalised using empirical biomass equation for *Mahonia*. As estimated biomass on the basis of
345 empirical equations is generally found to be higher than field observed values, all outputs were
346 multiplied by a compensatory adjustment factor of 0.8 following Nowak (1994). Similar to the i-Tree

347 Eco approach, the total biomass estimates were further multiplied by biomass adjustment factor
348 (ranges from 0-1) to adjust for the tree condition as follows: fair to excellent condition – 1, poor
349 condition – 0.76, critical condition – 0.42, dying – 0.15, dead – 0.

350

351 *3.2.3 Thermal Comfort Potential*

352 The peculiar role of street vegetation in shading the buildings and the paved surface in its vicinity
353 during sunlit hours has been considered as a proxy for its TCP. Direct measurements of air, mean
354 radiant or surface temperatures were not undertaken during this study as sufficient inferences have
355 been drawn in previous experimental studies, both in the UK (Armston et al., 2013b) and elsewhere
356 (Shashua-Bar et al., 2010a,b). For the majority of the tree species the two parameters characterising
357 TCP (canopy area, LAI) were acquired directly from the i-Tree inventory (Nowak et al., 2006; USDA,
358 2008). The canopy characteristics of shrubs included in this study were derived from direct field
359 measurements.

360

361 *3.2.4 Noise Attenuation Potential*

362 Inferences on acoustic performance of roadside plants have shown them more effective in noise
363 attenuation if their orientation is lower towards the noise and higher towards the receptors, enabling
364 noise absorbance as well as deflection (Pathak et al., 2011). However, the majority of trees grown in
365 street environments are meant to be away from the roads, mainly to avoid unwanted mess creation on
366 pavements and streets and taking into consideration the health and safety of the road users. As a
367 compromise, all vegetation within 50 m of the street verges in our case study area were considered to
368 meet the criteria of suitable noise buffers. While no actual measurement of noise attenuation was
369 conducted, inferences based on previous studies (Huddart, 1990; Ozer et al., 2007; Pathak et al., 2011)
370 were used to identify medium-to-low height denser vegetation with vertically uniform leaf
371 distribution as better candidates for noise attenuation compared to taller trees with prominent trunk
372 space and distinct crown. Canopy densities of the tree species were characterised using three stand
373 parameters (average leaf biomass, canopy area, height of stand), acquired mainly from the i-Tree
374 inventory data (Nowak et al., 2006; USDA, 2008). The canopy characteristics of the shrubs and the
375 IAL for all the species were obtained from direct field observations.

376

377 *3.2.5 Biomass Energy Potential*

378 For estimating the BEPs, the required constituent chemical composition of woody biofuels - *C*, *H*, *O*,
379 *N*, *S* and *Ash* (see **Section 2.5**) of the selected species typically representative of temperate climates in
380 Europe and North America were acquired from literature survey (**Table 2**) (Obernberger et al., 2005;
381 AIEL, 2008; Tumuluru et al., 2011). Those species which have not been exclusively listed in the
382 literature were approximated as typical values of the following categories – virgin wood thinning

383 (coniferous or deciduous wood/ logging residues), wood chips, short rotation coppice pruning –
384 provided in AIEL (2008).

385

386 *3.2.6 Environmental Stress Tolerance*

387 In order to estimate the ESTs, a sampling protocol was adapted to ensure that the species were
388 subjected to similar stress environments i.e. exposure to traffic air pollutants, soil conditions and
389 insolation levels, and negligible spatial heterogeneity. This was considered since environmental
390 factors like soil, rainfall, temperature are important parameters influencing the pollution tolerance of
391 vegetation (Mickler et al., 2003). Ascorbic acid content of leaf samples was estimated following
392 Queval and Noctor (2007). Total chlorophyll content of the leaves was estimated using the technique
393 adopted from Yan-Ju and Ding (2008). The leaf pH was determined following Prajapati and Tripathi
394 (2008). The relative water content, estimated following Pathak et al. (2011), served as a measure of
395 plant stress from exposure to pollutants. Standard protocols and formulations for sampling and
396 analysis of the four constituent parameters are provided in **Table 2**.

397 For estimation of EST, conducting a long-term sampling campaign for all the species studied over
398 different seasons was considered ambitious, mainly owing to the difficulty in associating
399 environmental stressors with the evergreens during no-leaf periods of deciduous species. As a
400 substitute, we considered it appropriate to set the start of the spring foliation season for the deciduous
401 species as the benchmark for representative estimation of the EST. Thereafter, field sampling of all
402 the constituent parameters for the studied species were obtained in three stages (late-spring, mid-
403 summer, early-autumn), followed by laboratory analyses (Tiwary et al., 2015).

404 *<place Table 2 somewhere here>*

405

406

407 **4. Results and Discussion**

408 *4.1. Performance index*

409 The Performance Index (PI) framework was successfully applied to the species included in the case
410 study, demonstrating its capabilities for conducting a comprehensive evaluation of street trees. For
411 each species first the values of the seven traits were quantified through the proposed methodology and
412 then they were harmonised using the gradation scheme (**Table A.1**) to obtain their corresponding PI
413 scores (**Table 3**). Despite variations in constituent traits, a number of species attain similar PI score
414 (mostly in 13-17 range), primarily owing to different combinations of individual gradations for the
415 seven traits considered. This is crucial for developing a sustainable streetscape green infrastructure
416 and reflects the strength of the PI approach in incorporating multi-dimensional attributes of the
417 species in ensuring their worthiness of streetscaping. It is worth mentioning that the pollution flux
418 potential (PFP) is the net effect of the level of pollutant release and/or deposited on the species whilst

419 the environmental stress tolerance (EST) is the measure of its pollution tolerance. The lower PFPs for
420 some species are mainly attributed to their net effect on air pollution flux to the local environment, i.e.
421 the fact that their pollution sink potentials (P_{dep}) are offset by their BVOC emissions (P_{emit}) potentials.
422 For example, the lower PFPs for Sweetgum and SRC Willow (almost negligible) are mainly owing to
423 the resultant effects of pollutant deposition and emission [Sweet gum: $P_{emit}(373.75 \text{ g y}^{-1})$, $P_{dep}(368.63$
424 $\text{g y}^{-1})$; PFP(-0.03 ~ 0.0) (since $P_{emit} > P_{dep}$) and SRC Willow: $P_{emit}(1506.00 \text{ g y}^{-1})$, $P_{dep}(1591.87 \text{ g y}^{-1})$;
425 PFP (0.093 ~ 0.1) (since $P_{emit} < P_{dep}$)]. The high ESTs of London Plane, Turkish Hazlenut,
426 Horsechestnut, Spruce, Hornbeam, Ash and Lime demonstrate their high pollution tolerance,
427 corroborating with previous studies on their worthiness as tolerant street vegetation (Beckett et al.,
428 2000; Sæbø et al., 2005; Peachey et al., 2009). The thermal comfort potentials (TCPs) are typically
429 higher for trees with large crowns, for example Beech, Horsechestnut, Spruce. London Plan,
430 Sycamore. The noise attenuation potential (NAP) is consistently poor for the majority of species,
431 except for Spruce and the shrubs, which is attributed mainly to their foliage density characteristics.
432 The carbon sequestration and bioenergy provision (CSP, BEP respectively) capabilities seem closely
433 related to each other with London Plane and Willow showing best suitability. For shrubs, the PI
434 scores are dominated by their high CPF and modest NAP and EST. The latter two are typical for the
435 evergreen shrubs and considered vital traits for ensuring their suitability as streetscape vegetation.
436 Overall, among trees Norway spruce (evergreen species) appears to be the most favorable for
437 streetscapes, with high scores across most of the evaluated traits, except CSP and BEP. This is
438 followed by Willow, Maple, Hazlenut, Hornbeam, Ash, London Plane, Lime and Horsechestnut.
439 Beech and Sweetgum are the only two species attaining unfavourable PI score for streetscaping. The
440 case of Beech is unique – it does score high on its multi-functionality traits so definitely is a high-
441 performing species overall for general urban planting (e.g. parklands, greenspace, woodlands, etc.),
442 but it does not seem favorable for the street environments, solely owing to its unfavorable CPF score.
443 On the other hand, the case of Sweetgum is completely different, which despite exhibiting a
444 favourable CPF fails to acquire a higher PI owing to its lower PFP (being high BVOC emitter).

445 <place Table 3 somewhere here>

446

447 4.2 Merits and limitations

448 The proposed PI framework aims to develop high-performing streetscape vegetation. It is noteworthy
449 that the PI is an indicative metric, specifically meant for streetscape vegetation under European
450 conditions. It should not be interpreted as absolute values, and in no way should be treated as a ‘one-
451 size-fits-all’ blueprint for urban vegetation in general. The approach is still shy of being considered
452 comprehensive, in particular lacking supporting information on issues of storm water run-off/ flood-
453 risk mitigation and resilience therefrom. We acknowledge the use of inventoried data while evaluating

454 the constituent traits of the PI could be over- or under-estimating the resultant values. Albeit, the
455 inventory generated from the i-Tree Eco model is the most extensive publicly-available dataset thus
456 far (USDA, 2008), enabling screening level assessments to explore the trends without excessive
457 dependence on the experimental resources. Nevertheless, more ambitious assessments of streetscape
458 should follow representative evaluation of the constituent traits using the PI methodology. This could
459 also involve detailed analyses of site-specific samples corresponding to the study area's tree species,
460 climate, seasonality, management practice, etc. It is also noteworthy that the units of the traits are to
461 be strictly adhered to for consistency in allocation of representative grading score (**Table A.2**), failing
462 which will yield an anomalous PI score. The CSP estimations are based on empirical equations
463 specific to Europe for the majority of the species, however, a small number of species with no
464 Europe-specific information have been approximated using general equations. As such, this
465 introduces some uncertainty in the calculations, but for the added benefit of allowing a much broader
466 screening assessment of popular street vegetation this has been accepted as an affordable trade-off.
467 The derivations used for estimating TCP and NAP are purely indicative of the trends, based on their
468 characterising parameters as reported in the recent literature.

469 Another important limitation of the proposed PI approach, especially relevant for temperate
470 landscapes, is its abstract species-specific PI scoring for single street vegetation, which assumes a
471 steady foliage profile, rather than incorporating a mixed-species stand with a seasonally dynamic
472 vertical foliage profile and its corresponding phytological responses to the different seasons (spring-
473 summer: predominantly sun-lit with optimal foliage performance; autumn-winter: predominantly
474 over-casted or snow-laden with underperforming foliage). This issue affects both the deciduous and
475 the evergreen species, albeit it has more contrasting responses from the cyclic foliation and defoliation
476 of the deciduous species. We envisage this limitation may not be fully overcome. However, this could
477 be addressed by adequately accounting for the foliage and the seasonal dynamics in terms of a
478 weighted PI, hereafter referred to as $PI_{Effective}$. This is intended to overcome the issue of skewing the
479 species selection process by under or over-estimating the PIs of deciduous species over evergreen
480 species. For example, a deciduous species may have a higher peak PI during optimal foliage
481 performance over late-spring/summer, whereas an evergreen species may have consistently lower PI.
482 But owing to leaf abscission in the former case its $PI_{Effective}$ will be lower. Hypothetically, it implies
483 that although a deciduous species can have high PI values during the summer months, overall an
484 evergreen species can still have higher $PI_{Effective}$, owing to its consistent foliage profile capable of
485 continuing to perform under seasonal weather perturbations and extreme events (severed rain/storm,
486 snow, flood, draught, etc.) over the year (**Figure 1**). However, thorough assessment of this aspect of
487 the PI has been considered beyond the scope of this study.

488 <place Figure 1 somewhere here>

489 The gradations applied to convert the finite estimates for the constituent traits are subjective; a
490 uniform scaling has been adopted, reflecting the patterns reported in the literature, to alleviate this
491 issue. Further, our evaluations did not include lateral issues arising from unwanted mess creation on
492 pavements and in streets by some trees from droppings of fruits and foliage (e.g. *Prunus* (Ornamental
493 Cherry), or brittle limbs (e.g. *Robinia pseudoacacia* (Locust Tree), *Fraxinus angustifolia* 'Raywoodii'
494 (Claret Ash)). Root system is another important consideration, specific to the context of climate
495 change resilience of streetscape vegetation, with emerging trends suggesting vegetation with invasive
496 rooting systems (e.g. *Populus* (Poplar or Aspen), *Salix* (Willow)) and those with shallow rooting
497 systems (e.g. *Prunus* (Ornamental Cherry), *Betula* (Birch)) unfit for street environments. However,
498 the PI framework does not account for these aspects of streetscape vegetation, owing to limited
499 information on conducting a comprehensive evaluation across all the candidate species as yet.

500

501 **5. Conclusions and future directions**

502 Our study demonstrates development and application of a Performance Index (PI) for promoting
503 multi-functional and resilient urban streetscape vegetation, mainly aiming to maximise their service to
504 the urban community while ensuring their prolonged existence. Through a case study, conducted for a
505 real road-side environment comprising of fifteen trees and shrubs species, a mix of small-to-medium
506 size trees and evergreen shrubs is identified suitable for developing multi-functional streetscape
507 vegetation. The premise of the PI approach is that the vegetation species must be well-suited to the
508 specific growing conditions and resilient to threats from pests, drought, storms, etc., otherwise
509 functional performance is moot. It is noteworthy that this study only evaluated the direct energy
510 recovery from the biomass (in terms of calorific value). A more holistic evaluation in the next step
511 warrants extending the assessment framework to include additional traits, such as rain water
512 harvesting, flood risk aversion, nutrient recovery via composting and/or advanced bio refinery
513 processes (mainly for extraction of value-added chemicals from the biomass), etc. Lateral assessment
514 of roadside vegetation as scavengers of nutrients, could also be twinned towards promoting an
515 innovative street vegetation regime, dominated by species with low BVOC emissions, but at the same
516 time with accelerated response to N-deposition in terms of enhanced growth. Such managed street
517 environments would enhance nutrient utilisation capacity in a closed-system, further boosting their PI
518 through positive contributions. Our PI has implications for developing more resilient streetscape green
519 infrastructure, specifically in the context of scattered urbanisation pattern with low-density
520 development, commonly witnessed in the peri-urban regions.

521

522

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536

537 7. References

- 538 Adams, J.C., Lockaby, B.G., 1988. Variability of understory sweetgum biomass relationships. South.
539 J. Appl. For. 12, 5-7.
- 540 Aguaron, E., McPherson, G., 2012. Comparison of methods for estimating carbon dioxide storage by
541 Sacramento's urban forest. In: R. Lal, B. Augustin, editors, Carbon Sequestration in Urban
542 Ecosystems. Springer.
- 543 AIEL, 2008. Wood fuels handbook. Italian Agroforestry Energy Association, Padua (Italy).
544 www.biomassstradecentres.eu (accessed 20.04.14).
- 545 Akbari, H, Pomerantz M, Taha H., 2001. Cool surfaces and shaded trees to reduce energy use and
546 improve air quality in urban areas. Sol. Energy 70, 295–310.
- 547 Annighöfer, P., Mölder, I., Zerbe, S., Kawaletz, H., Terwei, A., Ammer, C., 2012. Biomass functions
548 for the two alien species *Prunus serotina* Ehrh. and *Robinia pseudoacacia* L. in floodplain forests of
549 Northern Italy. Eur. J. For. Res. 131, 1619-1635.
- 550 Armson, D., Stringer, P., Ennos, A.R., 2013a. The effect of street trees and amenity grass on urban
551 surface water runoff in Manchester, UK. Urban For. Urban Gree. 12, 282–286.
- 552 Armson, D., Rahman, M.A., Ennos, A.R., 2013b. A comparison of the shading effectiveness of five
553 different street tree species in Manchester, UK. Arbor. Urban For. 39(4), 157–164.
- 554 Barber, P.A., Paap, T., Burgess, T.I., Dunstan, W., Hardy, G.S.J., 2013. A diverse range of
555 Phytophthora species are associated with dying urban trees. Urban For. Urban Gree. 12(4), 569-575.
- 556 Bassuk, N., Deanna, F.C., Marranca, B.Z., Barb, N., 2009. Recommended Urban Trees: Site
557 Assessment and Tree Selection for Stress Tolerance. Urban Horticulture Institute, Cornell University,
558 Ithaca, NY.
- 559 Beckett, K.P., Freer-Smith, P.H., Taylor G., 2000. Effective tree species for local air-quality
560 management. J. of Arboriculture, 26 (1): 12–19.

561 Bernhardt-Römermann, M., Kirchner, M., Kudernatsch, T., Jakobi, G., Fischer A., 2006. Changed
562 vegetation composition in coniferous forests near to motorways in Southern Germany: the effects of
563 traffic-born pollution. *Environ. Pollut.* 143, 572-581.

564 Bignal, K.L., Ashmore, M.R., Headley, A.D., 2008. Effects of air pollution from road transport on
565 growth and physiology of six transplanted bryophyte species. *Environ. Pollut.* 156(2), 332-340.

566 BISIPLAN, 2012. The Bioenergy System Planners Handbook web-based handbook,
567 <http://bisiplan.bioenarea.eu/> (accessed: 12.08.14).

568 Britt, C., Johnston, M., 2008. *Trees in Town II A New Survey of Urban Trees in England and their
569 Condition and Management.* Department for Communities and Local Government, London.

570 Buccolieri, R., Salim, S.M., Leo, L.S., Di Sabatino, S., Chan, A., Ielpo, P., de Gennaro, G., Gromke,
571 C., 2011. Analysis of local scale tree-atmosphere interaction on pollutant concentration in idealized
572 street canyons and application to a real urban junction. *Atmos. Environ.* 45, 1702-1713.

573 Cairns, M.A., Brown, S., Helmer, E.H., Baumgardner, G.A., 1997. Root biomass allocation in the
574 world's upland forests. *Oecologia* 111, 1-11.

575 Calfapietra, C., Fares, S., Manes, F., Morani, A., Sgrigna, G., Loreto, F., 2013. Role of biogenic
576 volatile organic compounds (BVOC) emitted by urban trees on ozone concentration in cities: a
577 review. *Environ. Pollut.* 183, 71-80.

578 Calfapietra, C., Peñuelas, J., Niinemets, Ü., 2015. Urban Plant Physiology: adaptation-mitigation
579 strategies under permanent stress. *Trends Plant Sci.* 20(2), 72-75.

580 Chaulya, S.K., 2004. Assessment and Management of air quality for an opencast coal mining area. *J.
581 Environ. Manage.* 70, 1-14.

582 Chojnacky, D.C., Heath, L.S., Jenkins, J.C., 2014. Updated generalized biomass equations for North
583 American tree species. *Forestry* 87, 129-151.

584 Churkina, G., Grote, R., Butler, T.M., Lawrence, M., 2015. Natural selection? Picking the right trees
585 for urban greening. *Environ. Sci. Policy* 47, 12-17.

586 Clark, C., Adriaens, P., Talbot, F.B., 2008. Green roof valuation: a probabilistic economic analysis of
587 environmental benefits. *Environ. Sci. Technol.* 42(6), 2155-2161.

588 CLG, 2007. *Climate Change and Urban Green Spaces. Neighbourhoods, Cities and Regions Analysis
589 Division.* Communities and Local Government, London, UK.

590 Currie, B. A., & Bass, B., 2008. Estimates of air pollution mitigation with green plants and green
591 roofs using the UFORE model. *Urban Ecosyst.* 11(4), 409-422.

592 Davies, Z.G., Edmondson, J.L., Heinemeyer, A., Leake, J.R., Gaston, K.J., 2011. Mapping an urban
593 ecosystem service: quantifying above-ground carbon storage at a city-wide scale. *J. Appl. Ecol.* 48(5),
594 1125-1134.

595 Dawe, G.F.M., 2011. Street trees and the urban environment. In: *The Routledge Handbook of Urban
596 Ecology*, Routledge, Taylor & Francis group, Abingdon, UK.

597 de Richter, D.B., Jenkins, D.H., Karakash, J.T., Knight, J., McCreery, L.R., Nemestothy, K.P., 2009.
598 *Wood energy in America.* *Science* 323, 1432-1433.

599 Demuzere, M., Orru, K., Heidrich, O., Olazabal, E., Geneletti, D., Orru, H., Bhave, A.G., Mittal, N.,
600 Feliu, E., Faehnle, M., 2014. Mitigating and adapting to climate change: Multi-functional and multi-
601 scale assessment of green urban infrastructure. *J. Environ. Manag.* 146, 107-115.

602 Dobbs, C., Escobedo, F.J., Zipperer, W.C., 2011. A framework for developing urban forest ecosystem
603 services and goods indicators. *Landscape Urban Plan.* 99(3-4), 196-206.

604 Escobedo, F., Varela, S., Zhao, M., Wagner, J.E., Zipperer, W., 2010. Analyzing the efficacy of
605 subtropical urban forests in offsetting carbon emissions from cities. *Environ. Sci. Pol.* 13, 362-372.

606 Forest Research, 2014. The Right Trees for Changing Climate Database. url:
607 <http://www.righttrees4cc.org.uk/about.aspx> (accessed: 10.05.15).

608 Foster, J., Lowe, A., Winkelman, S., 2011. The value of green infrastructure for urban climate
609 adaptation. url: http://dev.cakex.org/sites/default/files/Green_Infrastructure_FINAL.pdf (accessed:
610 16.03.15).

611 Getter, K.L., Rowe, D.B., 2006. The role of extensive green roofs in sustainable development.
612 *Horticultural Sci.* 41(5), 1276-1285.

613 Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., Theuray, N., Lindley, S.J., 2008. Characterising the
614 urban environment of UK cities and towns: a template for landscape planning. *Landscape Urban Plan.*
615 87, 210–222.

616 Gillner, S., Vogt, J., Tharang, A., Dettmann, S., Roloff, A., 2015. Role of street trees in mitigating
617 effects of heat and drought at highly sealed urban sites. *Landscape Urban Plan.* 143, 33-42.

618 Gromke, C., Ruck, B., 2009. Effects of trees on the dilution of vehicle exhaust emissions in urban
619 street canyons. *Int. J. Environ. Waste Manage.* 4, 225–242.

620 Gromke, C., Blocken, B., 2015. Influence of avenue-trees on air quality at the urban neighborhood
621 scale. Part II: Traffic pollutant concentrations at pedestrian level. *Environ. Pollut.* 196, 176-184.

622 Guenther, A., 2013. Biological and chemical diversity of biogenic volatile organic emissions into the
623 atmosphere. *ISRN Atmos. Sci.*, 27 (<http://dx.doi.org/10.1155/2013/786290>).

624 Harris, T.B., Manning, W.J., 2010. Nitrogen dioxide and ozone levels in urban tree canopies. *Environ.*
625 *Pollut.* 158(7), 2384-2386.

626 Hall, J.M., Handley, J.F., Ennos, A.R., 2012. The potential of tree planting to climate-proof high
627 density residential areas in Manchester, UK. *Landscape Urban Plan.* 104(3), 410-417.

628 Hawkesbury City Council, 2010. Hawkesbury City Council Roadside Vegetation Management Plan.
629 Hawkesbury, Australia. url: www.hawkesbury.nsw.gov.au (accessed: 15.08.14).

630 Heidrich, O., Dawson, R.J., Reckien, D., Walsh, C.L., 2013. Assessment of the climate preparedness
631 of 30 urban areas in the UK. *Climatic Change* 120(4), 771-784.

632 Hofman, J., Samson, R., 2014. Biomagnetic monitoring as a validation tool for local air quality
633 models: A case study for an urban street canyon. *Environ. Int.* 70, 50-61.

634 Ignatieva, M., Stewart, G.H., Meurk, C., 2010. Planning and design of ecological networks in urban
635 areas. *Lands. Ecol. Eng.* 7(1), 17-25.

636 Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2003. National-scale biomass estimation
637 for United States tree species. *For. Sci.* 49, 12–35.

638 Jim, C.Y., Chen, W.Y., 2008. Pattern and divergence of tree communities in Taipei’s main urban
639 green spaces. *Landscape Urban Plan.* 84(3-4), 312-323.

640 Jim, C.Y., Chen, W.Y., 2009. Ecosystem services and valuation of urban forests in China. *Cities*,
641 26(4), 187-194.

642 Kendal, D., Williams, N.S., Williams, K.J., 2012. A cultivated environment: Exploring the global
643 distribution of plants in gardens, parks and streetscapes. *Urban Ecosyst.* 15(3), 637-652.

644 Kenney, W.A., van Wassenae, P.J., Satel, A.L., 2011. Criteria and indicators for strategic urban
645 forest planning and management. *Arbor. Urban For.* 37(3), 108–117.

646 Kwak, K.H., Baik, J.J., 2014. Diurnal variation of NO_x and ozone exchange between a street canyon
647 and the overlying air. *Atmos. Environ.* 86, 120-128.

648 LAEC, 2007. Chainsaw massacre: a review of London’s street trees. Greater London Authority,
649 London.

- 650 Lau, O.W., Luk, S.F., 2001. Leaves of *Bauhinia blakeana* as indicators of atmospheric pollution in
651 Hong Kong. *Atmos. Environ.* 35, 3113-3120.
- 652 Leuzinger, S., Vogt, R., Körner, R., 2010. Tree surface temperature in an urban environment. *Agric.*
653 *For. Meteorol.* 150, 56-62.
- 654 Maleki, K., Hosseini, S.M., Nasiri, P., 2010. The effect of pure and mixed plantations of *Robinia*
655 *Pseudoacasia* and *Pinus Eldarica* on traffic noise decrease. *Int. J. Environ. Sciences*, 1(2), 213-224.
- 656 McDonald, A.G., Bealey, W.J., Fowler, D., Dragosits, U., Skiba, U., Smith R.I., Donovan, R.G.,
657 Brett, H.E., Hewitt, C.N., Nemitz, E., 2007. Quantifying the effect of urban tree planting on
658 concentrations and depositions of PM₁₀ in two UK conurbations. *Atmos. Environ.* 41(38), 8455-8467.
- 659 McPherson, E.G., 2010. Tools for valuing tree and park services. *Western Arborist*, 58-63.
- 660 Mickler, R., McNulty, S., Birdsey, R., 2003. Responses of forests in the eastern US to air pollution
661 and climate change. *Dev. Environ. Sci.* 3, 345-358.
- 662 Moreno, E., Sagnotti, L., Dinarès-Turell, J., Winkler, A., Cascella, A., 2003. Biomonitoring of Traffic
663 air pollution in Rome using magnetic properties of leaves. *Atmos. Environ.* 37, 2967-2977.
- 664 Northup, B.K., Zitzer, S.F., Archer, S., McMurtry, C.R., Boutton, T.W., 2005. Aboveground biomass
665 and carbon and nitrogen content of woody species in a subtropical thornscrub parkland. *J. Arid Env.*
666 62, 23-43.
- 667 Nowak, D.J., 1993. Atmospheric carbon reduction by urban trees. *J. Environ. Manage.* 37, 207-217.
- 668 Nowak, D.J., 1994. Atmospheric carbon dioxide reduction by Chicago's urban forest. In: E.G.
669 McPherson et al., editors, *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest*
670 *Climate Project*. USDA Forest Service General Technical Report NE-186, Radnor, PA. p. 83-94.
- 671 Nowak, D.J., Crane, D.E., 2002. Carbon storage and sequestration by urban trees in the USA.
672 *Environ. Pollut.* 116, 381-389.
- 673 Nowak, D.J., Crane, D.E., Stevens, J.C., 2006. Air pollution removal by urban trees and shrubs in the
674 United States. *Urban For. Urban Gree.* 4(3-4), 115-123.
- 675 Nowak, D.J., Eric, J., Greenfield, R.E., Hoehn, E.L., 2013. Carbon storage and sequestration by trees
676 in urban and community areas of the United States. *Environ. Pollut.* 178, 229-236.
- 677 Nowak, D.J., Hirabayashi, S., Bodine, A., Greenfield, E., 2014. Tree and forest effects on air quality
678 and human health in the United States. *Environ. Pollut.* 193, 119-129.
- 679 Obernberger, I., Brunner, T., Bärnthaler, G., 2005. Chemical properties of solid biofuels –
680 significance and impact. Institute for Resource Efficient and Sustainable Systems, Graz, Austria.
- 681 Ozer, S., Akif Irmak, M., Yilmaz, H., 2007. Determination of roadside noise reduction effectiveness
682 of *Pinus sylvestris L.* and *Populus nigra L.* in Erzurum, Turkey. *Environ. Monitoring and Assess.* 1,
683 11-18.
- 684 Pandit, R., Polyakov, M., Tapsuwan, S., Moran, T., 2013. The effect of street trees on property value
685 in Perth, Western Australia. *Landscape Urban Plan.* 110, 134-142.
- 686 Pathak V., Tripathi, B.D., Mishra, V.K., 2011. Evaluation of Anticipated Performance Index of some
687 tree species for green belt development to mitigate traffic generated noise. *Urban For. Urban Gree.*
688 10(1), 61-66.
- 689 Pauleit, S., 2003. Urban street tree plantings: identifying the key requirements. *Proceedings of the*
690 *ICE-Municipal Engineer*, 156(1), 43-50.
- 691 Peachey, C.J., Sinnett, D., Wilkinson, M., Morgan, G.W., Freer-Smith, P.H., Hutchings, T.R., 2009.
692 Deposition and solubility of airborne metals to four plant species grown at varying distances from two
693 heavily trafficked roads in London. *Environ. Pollut.* 157(8), 2291-2299.

- 694 Plant for the Planet, 2014. Billion Tree Campaign. <http://www.plant-for-the-planet.org/> (accessed:
695 12.11.14).
- 696 Prajapati, S.K., Tripathi, B.D., 2008. Anticipated Performance Index of some tree species considered
697 for green belt development in and around an urban area: A Case study of Varanasi city, India. *J.*
698 *Environ. Manage.* 88, 1343-1349.
- 699 Profous, G.V., Rowntree, R.A., Loeb, R.E., 1998. The urban forest landscape of Athens, Greece:
700 aspects of structure, planning and management. *Arbor. J.* 12, 83–108.
- 701 Queval, G., Noctor, G., 2007. A plate reader method for the measurement of NAD, NADP,
702 glutathione, and ascorbate in tissue extracts: Application to redox profiling during *Arabidopsis* rosette
703 development. *Anal. Biochem.* 363(1), 58-69.
- 704 Quigley, M.F., 2004. Street tree and rural conspecifics: will long-lived trees reach full size in urban
705 conditions? *Urban Ecosystems* 7, 29–39.
- 706 Randrup, T.B., McPherson, E.G., Costello, L.R., 2001. A review of tree root conflicts with sidewalks,
707 curbs, and roads. *Urban Ecosystems* 5, 209-225.
- 708 Rao, P.S., Gavane, A.G., Ankam, S.S., Ansari, M.F., Pandit, V.I., Nema, P., 2004. Performance
709 evaluation of a green belt in petroleum refinery: a case study. *Ecol. Eng.* 23, 77-84.
- 710 Raupp, M.J., Cumming, M.J., Raupp, E.C., 2006. Street tree diversity in eastern North America and
711 its potential for tree loss to exotic borers. *Arbor. Urban For.* 32(6), 297–304.
- 712 Roloff, A., Korn, S., Gillner, S., 2009. The climate-species-matrix to select tree species for urban
713 habitats considering climate change. *Urban For. Urban Gree.* 8, 295–308.
- 714 Roy, S., Byrne, J., Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs,
715 and assessment methods across cities in different climatic zones. *Urban For. Urban Gree.* 11(4), 351-
716 363.
- 717 Sæbø, A., Borzan, Ž., Ducatillion, C., Hatzistathis, A., Lagerström, T., Supuka, J., Van Slycken, J.,
718 2005. The selection of plant materials for street trees, park trees and urban woodland. In: *Urban*
719 *forests and trees.* Springer Berlin Heidelberg, pp. 257-280.
- 720 Sagani, A., Hagidimitriou, M., Dedoussis, V., 2014. A study of burning olive tree pruning biomass for
721 electricity generation. (ed. The Swedish Bioenergy Association) *Proceedings of World Bioenergy*
722 *Conference, 3-5 Jun 2014 p. 66-70.* (www.worldbioenergy.com).
- 723 Salmond, J.A., Williams, D.E., Laing, G., Kingham, S., Dirks, K., Longley, I., Henshaw, G.S., 2013.
724 The influence of vegetation on the horizontal and vertical distribution of pollutants in a street canyon.
725 *Sci. Total Environ.*, 443: 287–298.
- 726 Shashua-Bar, L., Potchter, O., Bitan, A., Boltansky, D., Yaakov, Y., 2010a. Microclimate modelling
727 of street tree species effects within the varied urban morphology in the Mediterranean city of Tel
728 Aviv, Israel. *Int. J. Climatol.* 30, 44–57.
- 729 Shashua-Bar, L., Tsiros, I.X., Hoffman, M.E., 2010b. A modeling study for evaluating passive
730 cooling scenarios in urban streets with trees. Case study: Athens, Greece. *Building and Environ.*
731 45(12), 2798-2807.
- 732 Sjöman, H., Nielsen, A.B., 2010. Selecting trees for urban paved sites in Scandinavia – a review of
733 information on stress tolerance and its relation to the requirements of tree planners. *Urban For. Urban*
734 *Green.* 9, 281–293.
- 735 Setälä, H., Viippola, V., Rantalainen, A.L., Pennanen, A., Yli-Pelkonen, V., 2013. Does urban
736 vegetation mitigate air pollution in northern conditions? *Environ. Pollut.* 183, 104-112.
- 737 Shimano, K., 1997. Analysis of the relations between DBH and crown projection area using a new
738 model. *J. For. Res.* 2, 237-242.

- 739 Strovin, V.R., Jorgensen, A., Clayden, A., 2008. Street trees and stormwater management.
740 *Arboricultural Journal* 30(4):297-310.
- 741 Suchomel, C., Pyttel, P., Becker, G., Bauhus, J., 2012. Biomass equations for sessile oak (*Quercus*
742 *petraea* (Matt.) Liebl.) and hornbeam (*Carpinus betulus* L.) in aged coppiced forests in southwest
743 Germany. *Biomass Bioenerg.* 46, 722–730.
- 744 Tiwary, A., Sinnett, D., Peachey, C., Chalabi, Z., Vardoulakis, S., Fletcher, T., Leonardi, G., Grundy,
745 C., Azapagic, A., Hutchings, T.R., 2009. An integrated tool to assess the role of new planting in PM₁₀
746 capture and the human health benefits: A case study in London. *Environ. Pollut.* 157(10), 2645–2653.
- 747 Tiwary, A., Raje, V., Calfapietra, C., 2015. Assessment of urban vegetation pollution tolerance in
748 street environments. *Urban For. Urban Gree.* *Under review.*
- 749 Tratalos, J., Fuller, R.A., Warren, P.H., Davies, R.G., Gaston, K.J., 2007. Urban form, biodiversity
750 potential and ecosystem services. *Landscape Urban Plan.* 83, 308-317.
- 751 Truscott, A.M., Palmer, S.C.F., McGowan, G.M, Cape, J.N., Smart, S., 2005. Vegetation composition
752 of roadside verges in Scotland: the effects of nitrogen deposition, disturbance and management.
753 *Environ. Pollut.* 136, 109-118.
- 754 Tumuluru, J.S., Sokhansanj, S., Wright, C.T., Bordman, R.D., Yancey, N.A., 2011. A review on
755 biomass classification and composition, co-firing issues and pretreatment methods. ASABE Annual
756 International Meeting (Report no. INL/CON-11-22458) Louisville, Kentucky August 7–10.
- 757 USDA, 2008. i-Tree User's Manual. United States Department of Agriculture and Forest Service. url:
758 <http://www.itreetools.org/resources/manuals/i-Tree%20Eco%20Users%20Manual.pdf> (accessed:
759 12.06.13).
- 760 Vidrih, M., Vidrih, T., Kotar, M., 2009. In Slovenia: Management of intensive land use systems. In:
761 A. Rigueiro-Rodríguez et al., editors, *Agroforestry in Europe: current status and future prospects.*
762 Springer Science + Business Media, Dordrecht. p. 397–414.
- 763 Vlachokostas, C., Michailidou, A.V., Matziris, E., Achillas, C., Moussiopoulos, N., 2014. A multiple
764 criteria decision-making approach to put forward tree species in urban environment. *Urban Clim.* 10,
765 105-118.
- 766 Wagh, N.D., Shukla, P.V., Tambe, S.B., Ingle, S.T., 2006. Biological monitoring of roadside plants
767 exposed to vehicular pollution in Jalgaon city. *J. Environ. Biol.* 27, 419-421.
- 768 Wania, A., Bruse, M., Blond, N., Weber, C., 2012. Analysing the influence of different street
769 vegetation on traffic-induced particle dispersion using microscale simulations. *J. Environ. Manage.*
770 94, 91–101.
- 771 Williams, N.S.G., Schwartz, M.W., Vesk, P.A., Mccarthy, M.A., Hahs, A.K., Clemants, S.E., Corlett,
772 R.T., Duncan, R.P., Norton, B.A., Thompson, K., McDonnell, M.J., 2009. A conceptual framework
773 for predicting the effects of urban environments on floras. *J. Ecol.* 97(1), 4-9.
- 774 Wutzler, T., Wirth, C., Schumacher, J., 2008. Generic biomass functions for common beech (*Fagus*
775 *sylvatica*) in Central Europe: predictions and components of uncertainty. *Can. J. For. Res.*, 38:1661–
776 75.
- 777 Yang, J., McBride, J., Zhou, J., Sun, Z., 2005. The urban forest in Beijing and its role in air pollution
778 reduction. *Urban For. Urban Gree.* 3, 65-78.
- 779 Yan-ju, L., Ding, H., 2008. Variation in air pollution tolerance index of plants near a steel factory:
780 Implications for landscape-plant species selection for industrial areas. *WSEAS T. Environ. Dev.* 4(1),
781 24-32.
- 782 Young, R.F., 2011. Planting the living city. *J. Am. Plan. Assoc.* 77, 368–381.
- 783 Zhao, M., Kong, Z., Escobedo, F.J., Gao, J., 2010. Impacts of urban forests on offsetting carbon
784 emissions from industrial energy use in Hangzhou, China. *J. Environ. Manag.* 91(4), 807-813.

- 785 Zhao, J., Chen, S., Jiang, B., Ren, Y., Wang, H., Vause, J., Yu, H., 2013. Temporal trend of green
786 space coverage in China and its relationship with urbanization over the last two decades. *Sci. Total*
787 *Environ.* 442, 455–465.
- 788 Zianis, D., Muukkonen, P., Mäkipäänd, R., Mencuccini, M., 2005. *Silva Fennica. Monographs:*
789 *biomass and stem volume equations for tree species in Europe.* The Finnish Society of Forest Science,
790 The Finnish Forest Research Institute.

LIST OF TABLES

Table 1. Morphological definition of the street vegetation species used in evaluation.

Species	Average Stand height (m)	Average DBH (cm)	Average Street tree age [†] (yr)	Average LAI	IAL [‡]
Stand type: Trees					
Horsechestnut (<i>Aesculus hippocastanum</i>) ^a	16.70	63.90	90	5.55	0.58
Sycamore Maple (<i>Acer pseudoplatanus</i>) ^a	9.37	32.44	23	2.76	0.75
Hornbeam (<i>Carpinus betulus</i>) ^a	12.57	7.15	35	2.03	0.75
Turkish Hazel (<i>Corylus colurna</i>) ^a	13.03	14.73	15	3.02	0.60
Beech (<i>Fagus sylvatica</i>) ^a	19.5	99.10	234	6.12	0.75
Ash (<i>Fraxinus pennsylvanica</i>) ^a	11.84	24.39	38	4.11	0.58
Sweet gum (<i>Liquidambar styraciflua</i>) ^a	15.85	30.50	47	3.62	0.67
London Plane (<i>Platanus x acerifolia</i>) ^a	16.51	63.85	98	2.40	0.67
SRC Willow (<i>Salix viminalis</i>) ^a	10.17	11.15	20	2.31	0.75
Lime – Littleleaf Linden (<i>Tilia cordata</i>) ^a	7.64	24.32	17	3.87	0.60
Norway Spruce (<i>Picea abies</i>) ^b	13.4	44.4	50	9.80	1.00
Stand type: Shrubs					
Black Cherry (<i>Prunus serotina</i>) ^a	3.27	12.23	30	2.44	0.60
Berberis (<i>Berberis stenophylla</i>) ^b	2.25	7.25	15	3.27	1.00
Laurustinus (<i>Viburnum tinus</i>) ^b	5.20	8.3	10	3.52	1.00
Mahonia (<i>Mahonia japonica</i>) ^b	1.90	5.74	15	2.92	1.00

a = deciduous; *b* = evergreen.

[†] The life span for street trees is expected to be much shorter than their maximum biological potential reported for woodlands (Pauleit, 2003; USDA, 2008).

[‡] Intra-annual leaf cover.

Table 2. Constituent parameters and evaluation methods used for estimating the set of multi-functionality and resilience traits.

Trait	Constituent parameter	Method	Literature source
<i>Multi-functionality</i>			
Pollutant flux potential (PFP)	Leaf area index (LAI) ^a	Inventoried literature data	USDA (2008)
	Intra-annual leaf cover (IAL) ^b	Field survey	
	Pollutant deposition (P_{dep}) ^a (g yr ⁻¹)	Estimated as annual average total removal of CO, PM ₁₀ , NO ₂ , O ₃ , and SO ₂ per unit tress cover area (m ²)	Nowak et al. (2006); USDA (2008)
	Pollutant emission (P_{emi}) ^a (g yr ⁻¹)	Estimated as annual average total emission of isoprene, monoterpene, and other VOCs	USDA (2008)
Carbon sequestration potential (CSP) (kg yr⁻¹)	Diameter at breast height (DBH) ^b (cm)	Field survey	
	Height of crown base ^b (m)	Field survey	
	Above Ground Biomass (AGB) ^a (kg yr ⁻¹)	Estimated using DBH and stand height data in empirical biomass equations.	Various (see Appendix Table B.1)
Thermal Comfort Potential (TCP)[†]	Canopy area (m ²) ^a	Inventoried literature data	USDA (2008)
	Leaf area index (LAI) ^a		
Noise Attenuation Potential (NAP)[†]	Avg. leaf biomass (kg) ^a	Inventoried literature data	USDA (2008)
	Canopy area (m ²) ^a		
	Avg. stand height (m) ^a		
Biomass energy potential (BEP) (MJ yr⁻¹)	Chemical composition (C, H, O, N, S and Ash) ^a (% wt./wt. of dry biomass)	Acquired from the literature measurements based on elemental analysis following standard CEN/TS 14961:2005 (see Section 3.2 for details). Ash content measured in a furnace, adhering to standard DD CEN/TS 14775:2004.	Obernberger et al. (2005); AIEL (2008); Tumuluru et al. (2011)
	Heating values ^a (MJ kg ⁻¹)	Obtained from heating value of tree biomass on a dry basis, mainly the woody stock from chips, bark and pruning using literature data (see Section 2.3).	BISYPLAN (2012); Sagani et al. (2014)
<i>Resilience</i>			
Environmental stress tolerance	Leaf Ascorbic acid content ^b	Determined from spectrophotometric analysis of supernatant samples obtained	Keller and Schwager (1977);

(EST)	(mg g ⁻¹ fresh weight)	<p>from snap-frozen leaf discs using the formula:</p> $\frac{(E_0 - E_s - E_t) * V}{W \times 100} \times 100$ <p>where V is the volume of the extract, W is the weight of the leaf sample (g), and E₀, E_s and E_t are optical densities of blank sample, plant sample and sample with ascorbic acid respectively.</p>	Prajapati and Tripathi (2008); Pathak et al. (2011)
	Total chlorophyll content ^b (mg g ⁻¹)	Determined from spectrophotometric analysis of optical densities of solutions of leaf pigment extracts (obtained in dark to avoid photo-oxidation of pigments) at 645 and 663nm wavelengths (D ₆₄₅ and D ₆₆₃ respectively) using the formula: $1.62 (D_{645}) + 0.64 (D_{663})$	Prajapati and Tripathi (2008); Yan-ju and Ding (2008)
	Leaf pH ^b	Determined using a digital pH meter from supernatant samples of crushed and homogenized 0.5 g of leaf.	Prajapati and Tripathi (2008)
	Relative water content ^b (%)	<p>Calculated from leaf weight (LW) using the following formula:</p> $RWC = \frac{LW_{fresh} - LW_{dry}}{LW_{turgid} - LW_{dry}} \times 100$	Pathak et al. (2011)

^a Representative estimates based on literature data.

^b Direct field measurements.

[†] Parameters used for evaluation of qualitative trends only (see Sections 2.3 and 2.4).

Table 3. Estimation of performance index (PI) on the basis of the seven constituent traits as applied to fifteen street vegetation species in the case study area.

SPECIES Common Name	TRAITS-VALUES							TRAITS-GRADES							PI	
	PPF	CSP	TCP	NAP	BEP	EST	CPF	PPF	CSP	TCP	NAP	BEP	EST	CPF		
Horsechestnut	2.7	14.5	909.9	0.012	3.1	11.3	10.7	+++	++	++++	+	++	+++	--	→	13
Sycamore Maple	1.7	11.3	356.7	0.009	3.2	9.9	3.0	++	++	++	+	++	++	+++++	→	16
Hornbeam	1.4	1.9	161.4	0.007	1.0	10.8	0.9	++	+	+	+	+	+++	+++++	→	15
Turkish Hazelnut	3.0	4.4	138.1	0.025	1.5	11.6	1.9	+++	+	+	+	++	+++	+++++	→	16
Beech	3.7	17.0	951.1	0.012	0.9	9.9	19.3	++++	++	++++	+	+	++	-----	↓	8
Ash	2.2	3.9	230.8	0.013	0.8	10.3	2.9	+++	+	+	+	+	+++	+++++	→	15
Sweet gum	0.0	8.1	158.9	0.007	2.0	6.8	4.8	-	+	+	+	++	++	+++	↓	9
London Plane	2.3	21.6	359.7	0.003	5.4	14.3	10.5	+++	+++	++	+	+++	+++	-	→	14
Willow (SRC)	0.1	20.6	115.8	0.041	5.2	5.7	1.1	+	+++	+	++	+++	++	+++++	→	18
Lime (Littleleaf linden)	1.8	4.9	169.0	0.017	0.9	10.1	1.9	++	+	+	+	+	+++	+++++	→	14
Norway spruce	4.7	10.2	643.9	0.122	3.7	11.3	5.9	+++++	++	+++	+++++	++	+++	+++	↑	23
Black cherry	1.5	3.3	221.7	0.032	0.8	8.3	0.4	++	+	+	++	+	++	+++++	→	15
Berberis	1.4	0.0011	98.2	0.096	0.3	7.8	0.2	++	+	+	++++	+	++	+++++	→	17
Laurustinus	1.7	0.0013	102.7	0.093	0.4	8.5	0.4	++	+	+	++++	+	++	+++++	→	17
Mahonia	1.5	0.0009	112.4	0.102	0.3	6.7	0.1	++	+	+	+++++	+	++	+++++	→	18

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Figure 1

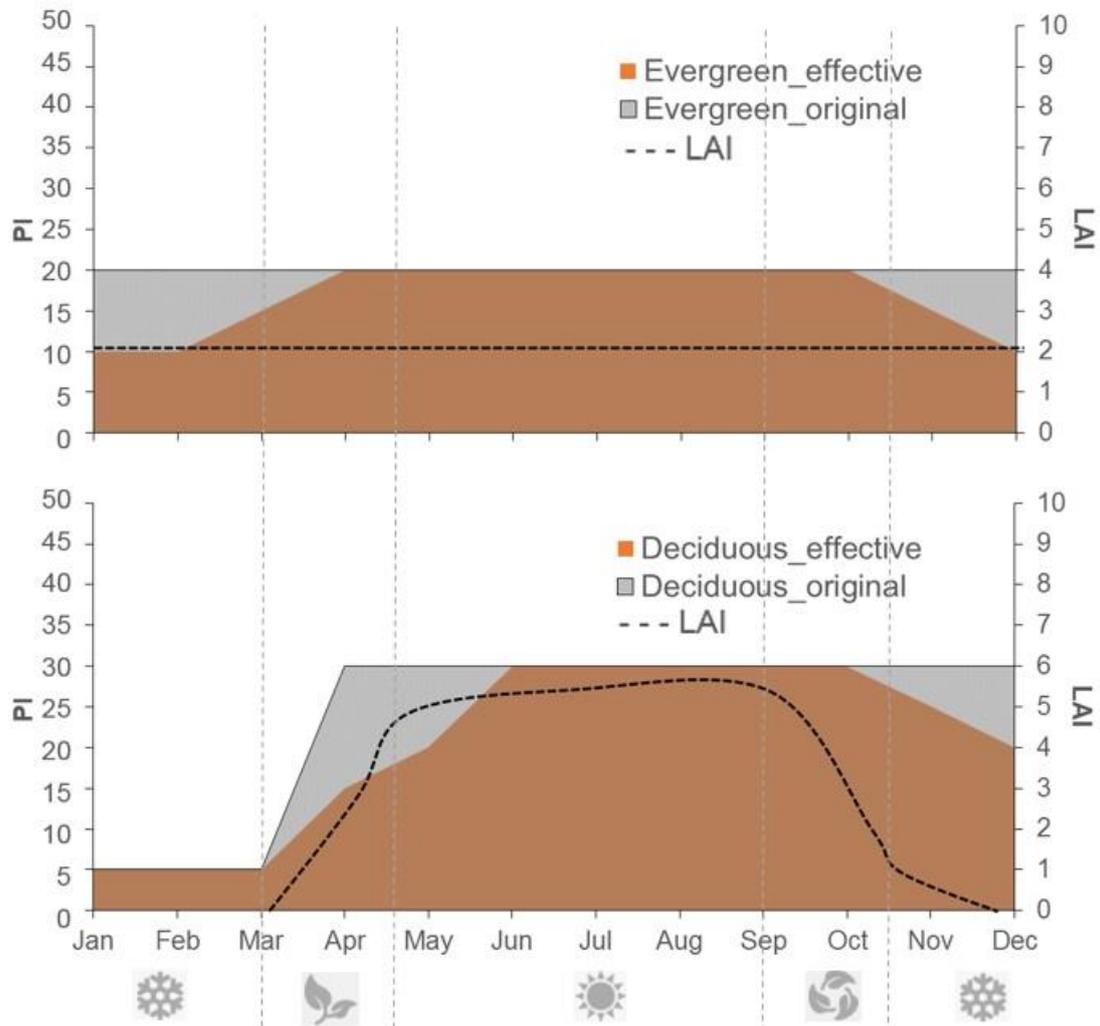


Figure 1. Schematic representation of the hypothetical $PI_{Effective}$ (foliage-cover weighted PI) of vegetation over four seasons, upper panel: evergreen; lower panel: deciduous [note: dotted line depicts LAI on the secondary y-axis, which is considered static for evergreen but variable over the growing season for deciduous species].

Appendix A

Table A.1. Gradation scheme applied across the spectrum of multi-functionality and resilience traits to harmonise the value-based estimates.

Trait	Assessment Criteria	Gradation
<i>Multi-functionality</i>		
Pollutant flux potential (PFP)	> 5.0	+++++
	5.0 to 4.1	+++++
	4.0 to 3.1	++++
	3.0 to 2.1	+++
	2.0 to 1.1	++
	1.0 to 0.1	+
	0.0 to -0.9	-
	-1.0 to -1.9	--
	-2.0 to -2.9	---
	-3.0 to -3.9	----
	-4.0 to -4.9	-----
	< -5.0	-----
Carbon sequestration potential (CSP) (kg yr ⁻¹)	> 0.0 to 10.0	+
	10.1 to 20.0	++
	20.1 to 30.0	+++
	30.1 to 40.0	++++
	40.1 to 50.0	+++++
	> 50.0	+++++
Thermal Comfort Potential (TCP) [†]	0.0 to 250	+
	251 to 500	++
	501 to 750	+++
	751 to 1000	++++
	1001 to 1250	+++++
	1251 to 1500	+++++
	> 1500	+++++
Noise Attenuation Potential (NAP) [†]	0.0 to 0.025	+
	0.026 to 0.050	++
	0.051 to 0.075	+++
	0.076 to 0.1	++++
	0.11 to 0.125	+++++
	> 0.125	+++++
Biomass energy potential (BEP) (MJ yr ⁻¹)	> 0.0 to 1.0	+
	1.1 to 5.0	++
	5.1 to 10.0	+++
	10.1 to 15.0	++++
	15.1 to 20.0	+++++
	> 20.0	+++++

Resilience

Environmental stress tolerance (EST)	> 0.0 to 5.0	+
	5.1 to 10.0	++
	10.1 to 15.0	+++
	15.1 to 20.0	++++
	20.1 to 25.0	+++++
	> 25.0	++++++

Canopy characteristics

Canopy projection factor (CPF)	> 0.0 to 1.5	++++++
	1.51 to 3.0	+++++
	3.1 to 4.5	++++
	4.51 to 6.0	+++
	6.1 to 7.5	++
	7.51 to 9.0	+
	9.1 to 10.5	-
	10.51 to 12.0	--
	12.1 to 13.5	-----
	13.51 to 15.0	-----
	>15.0	-----

† These are purely indicative trends, estimated using representative canopy and seasonal characteristics of species [note: units for indicative estimates of TCP and NAP are based on the dimensions of the parameters used and are respectively m² and kg m⁻³].

Table A.2. The decision matrix showing the resultant ranking score as equivalent Performance Index bands and their corresponding management decision interpretation for streetscaping.

Performance Index score	Decision category
< 5	Poor
5 - 10	Not recommended for street environments
> 10	Favourable for street environments

Appendix B

Table B.1. List of empirical biomass equations used to estimate the above ground biomass of different species.

Plant (Scientific Name)	Biomass Equation†	Parameters	Reference
Horsechestnut (<i>Aesculus hippocastanum</i>)	$\ln(\text{AGB}) = a + b * \ln(\text{dbh})$	a. -2.4800, b. 2.4835	Jenkins et al. (2003)
Sycamore Maple (<i>Acer pseudoplatanus</i>)	$\ln(\text{AGB}) = a + b * \ln(\text{dbh})$	a. -2.7018, b. 2.575	Zianis et al. (2005)
Hornbeam (<i>Carpinus betulus</i>)	$\text{AGB} = a * (\text{dbh})^b$	a. 0.258, b. 2.1748	Suchomel et al. (2012)
Turkish Hazelnut (<i>Corylus colurna</i>)	$\text{AGB} = a + b * (\text{dbh})^{1.99} * (\text{Height})^{3.0}$	a. 92.31, b. 2.7×10^{-9}	Vidrih et al. (2009)
Beech (<i>Fagus sylvatica</i>)	$\text{AGB} = a * (\text{dbh})^b * (\text{Height})^c$	a. 0.0523, b. 2.12, c. 0.655	Wutzler et al. (2008)
Ash (<i>Fraxinus pennsylvanica</i>)	$\ln(\text{AGB}) = a + b * \ln(\text{dbh})$	a. 2.4718, b. 2.5466	Zianis et al. (2005)
Sweet gum (<i>Liquidambar styraciflua</i>)	$\text{AGB} = a + b * (\text{dbh})^2 * \text{Height}$	a. -15.088, b. 0.1127	Adams and Lockaby (1988)
London Plane (<i>Platanus acerifolia</i>)	$\ln(\text{AGB}) = a + b * \ln(\text{dbh})$	a. -2.2118, b. 2.5349	Chojnacky et al. (2014)
Willow - SRC (<i>Salix viminalis</i>)	$\ln(\text{AGB}) = a + b * \ln(\text{dbh})$	a. -2.2094, b. 2.3867	Jenkins et al. (2003)
Lime - Littleleaf Linden (<i>Tilia cordata</i>)	$\ln(\text{AGB}) = a + b * \ln(\text{dbh})$	a. -2.6788, b. 2.4542	Zianis et al. (2005)
Norway spruce (<i>Picea abies</i>)	$\text{AGB} = a * (\text{dbh})^b$	a. 0.5769, b. 1.964	Zianis et al. (2005)
Black Cherry (<i>Prunus serotina</i>)	$a + b * (\text{dbh}) + c * (\text{dbh})^2$	a. 79.24, b. -12.78, c. 0.85	Annighöfer et al. (2012)
Berberis (<i>Berberis stenophylla</i>)	$\ln(\text{AGB}) = a + b * \ln(\text{dbh})$	a. 5.843, b. 1.715	Northup et al. (2005)
Laurustinus (<i>Viburnum tinus</i>)	$\ln(\text{AGB}) = a + b * \ln(\text{dbh})$	a. 5.843, b. 1.715	Northup et al. (2005)
Mahonia (<i>Mahonia japonica</i>)	$\ln(\text{AGB}) = a + b * \ln(\text{dbh})$	a. 5.843, b. 1.715	Northup et al. (2005)

† Biomass units for all species are kg/stand, except for shrub plants *Mahonia japonica*, *Berberis stenophylla*, *Viburnum tinus*, which are expressed in g stand⁻¹.