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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. Introduction

Streets usually cover more than a quarter of a city and offer opportunities for increasing tree density in the existing urban fabric. Urban proliferation, typically through scattered patterns of low-density developments, or infill of urban space with medium and high density dwellings, provide further potentials for boosting managed vegetation along streetscapes [1] comprising of roads, streets, sidewalks, squares, bridleways, etc. (LAEC, 2007; Jim and Chen, 2008; Stovin et al., 2008; Ignatieva et al., 2010; Dawe, 2011). Planting trees along streetscapes has been considered useful for improving urban health and wellbeing, especially in densely populated inner-city built environments characterised by space constraints and high pollution levels (Pauleit 2003; Roy et al., 2012; Vlachokostas et al., 2014). Through adequate policy measures and design strategies, street trees hold multifarious potentials for improving human comfort at modest costs, primarily through passive cooling, pollution alleviation (air, water, noise) and flood risk aversion (Shashua-Bar et al., 2010a; Armson et al., 2013a; Nowak et al., 2014; Gromke et al., 2015). Recent findings suggest public and private benefits of street trees in terms of their positive contributions to neighbourhood development and sustainability (Pandit et al., 2013; Salmond et al., 2013). Street vegetation already constitutes a substantial portion of green space cover in such regions globally, with reported tree densities of up to 158 and 300 stands per km of street respectively in Melbourne, Australia and Guangzhou, China (Kendal et al., 2011). In cities with heavy industrial or traffic activities, 'green belts' have been integral part of streetscapes (along ring roads and arterial/ trunk routes), primarily introduced to mitigate odour, noise and air pollution (Chaulya, 2004; Rao et al., 2004; Pathak et al., 2011).

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

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[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 *(× 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, HNO_2 and/or NH_3 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    $$PFP = \left(1 - {P_{emit}}\big/{P_{dep}}\right) \times LAI \times IAL \qquad\qquad [1]$$

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 10µm (PM10). 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 $$CSP = AGB \times TBCF \times C \qquad\qquad [2]$$

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 (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 $TCP \sim CanopyArea \times LAI$ [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 $NAP \sim \dfrac{Avg.LeafBiomass}{(CanopyArea \times Height)} \times IAL$ [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 $HHV = 0.341*C + 1.322*H - 0.12*(O+N) + 0.0686*S - 0.0153*Ash$ [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
$$BEP = LHV \times AGB = \left(HHV - \left(\frac{2.444 * 8.936 * H_{dry}}{100} \right) \times AGB \right) \qquad [6]$$

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

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

2.7 Crown Projection Factor

The Crown Projection Factor (CPF) has been considered an important trait in characterising streetscape vegetation. This is a measure of the lateral spread of a species at maturity, commonly expressed in terms of the canopy projection area in the arboriculture literature (Shimano, 1997). It is noteworthy that same tree species can potentially have different performance results for the majority of the earmarked traits along roadside vs. open parklands. Recent studies have reported large street trees as - obstacles to airflow, hampering the mixing of pollutants in poorly ventilated areas close to streets owing to reduced air exchange with the above-roof ambient environment (Gromke et al., 2009; Wania et al., 2012; Vos et al., 2013); damaging the road fabric owing to their deep rooting (Randrup et al., 2001). While on one hand, fastigiate (narrow) crowns are recommended as more effective in trapping the traffic pollutants (Darcy and Forrest 2010; Farahani et al. 2012), planting density and canopy coverage levels has been considered an important factor in noise reduction (Huddart, 1990; Pathak et al., 2011) and evapo-transpirational passive cooling (Shashus-Bar et al., 2010; Armson et al., 2013b) in urban streets. There is increasing emphasis on planting smaller tree species as street trees because they fit better into narrow pavements and are easier to manage (Britt and Johnston 2008). CPF has been inversely associated with fitness for street plantation and given overriding weightings (**Table A.1**) in the evaluation of PI, typically relevant for the narrow streets/roads in western European countries. This is meant to overcome the negative feedbacks to both the air and the soil environments in the street, potentially avoiding the competition between the road space and the kerbside vegetation. The CPF of a species (expressed as m^2) is directly proportional to its diameter at breast height (DBH) (typically for DBH < 100 cm; Shimano, 1997) and approximated as a coupled function of *DBH* and the stand height, *H* (in meters each) (**Eq. [8]**).

$$CPF = DBH \times H \qquad [8]$$

298

299

3. Case study

3.1 Site description and species selection

The case study site was located on an area spanning 250m×200m adjacent to a busy road network, connecting the suburbs to Newcastle-upon-Tyne city center, UK (54.979°N, 1.6111°W). An initial visual assessment of species abundance, proximity to the road and suitability for assessment was carried out to draw a shortlist of fifteen species, comprising of a mix of deciduous and evergreen trees and shrubs (**Table 1**). Inclusion of shrubs and forbs has been particularly recommended in the literature for a better understanding of the full suite of multi-functionality of the urban ecosystems (Dobbs et al., 2011). It is noteworthy that the life span for the majority of the street trees is much shorter than their biological potentials owing to harsh growing conditions in urban paved sites (for 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 HNO_2 and NH_3) decreasing more rapidly than those with a

321   lower deposition velocity (such as NO and NO_2) (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 climes 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

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

<place Table 3 somewhere here>

4.2 Merits and limitations

The proposed PI framework aims to develop high-performing streetscape vegetation. It is noteworthy that the PI is an indicative metric, specifically meant for streetscape vegetation under European conditions. It should not be interpreted as absolute values, and in no way should be treated as a 'one-size-fits-all' blueprint for urban vegetation in general. The approach is still shy of being considered comprehensive, in particular lacking supporting information on issues of storm water run-off/ flood-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 $PI_{Effectvie}$ 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>*

16

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

5. Conclusions and future directions

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

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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 (*Aesculus hippocastanum*)[a]	16.70	63.90	90	5.55	0.58
Sycamore Maple (*Acer pseudoplatanus*)[a]	9.37	32.44	23	2.76	0.75
Hornbeam (*Carpinus betulus*)[a]	12.57	7.15	35	2.03	0.75
Turkish Hazel (*Corylus colurna*)[a]	13.03	14.73	15	3.02	0.60
Beech (*Fagus sylvatica*)[a]	19.5	99.10	234	6.12	0.75
Ash (*Fraxinus pennsylvanica*)[a]	11.84	24.39	38	4.11	0.58
Sweet gum (*Liquidambar styraciflua*)[a]	15.85	30.50	47	3.62	0.67
London Plane (*Platanus x acerifolia*)[a]	16.51	63.85	98	2.40	0.67
SRC Willow (*Salix viminalis*)[a]	10.17	11.15	20	2.31	0.75
Lime – Littleleaf Linden (*Tilia cordata*)[a]	7.64	24.32	17	3.87	0.60
Norway Spruce (*Picea abies*)[b]	13.4	44.4	50	9.80	1.00
Stand type: Shrubs					
Black Cherry (*Prunus serotina*)[a]	3.27	12.23	30	2.44	0.60
Berberis (*Berberis stenophylla*)[b]	2.25	7.25	15	3.27	1.00
Laurustinus (*Viburnum tinus*)[b]	5.20	8.3	10	3.52	1.00
Mahonia (*Mahonia japonica*)[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
Multi-functionality			
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_{emit})[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] Leaf area index (LAI)[a]	Inventoried literature data	USDA (2008)
Noise Attenuation Potential (NAP)[†]	Avg. leaf biomass (kg) [a] Canopy area (m^2)[a] Avg. stand height (m) [a]	Inventoried literature data	USDA (2008)
	Intra-annual leaf cover (IAL)[b]	Field survey	
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)
Resilience			
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)	from snap-frozen leaf discs using the formula: $$\frac{\left(E_0 - E_s - E_t\right)*V}{W \times 100} \times 100$$ where V is the volume of the extract, W is the weight of the leaf sample (g), and E_0, E_s and E_t are optical densities of blank sample, plant sample and sample with ascorbic acid respectively.	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] (%)	Calculated from leaf weight (LW) using the following formula: $$RWC = \frac{LW_{fresh} - LW_{dry}}{LW_{turgid} - LW_{dry}} \times 100$$	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
	PFP	CSP	TCP	NAP	BEP	EST	CPF	PFP	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
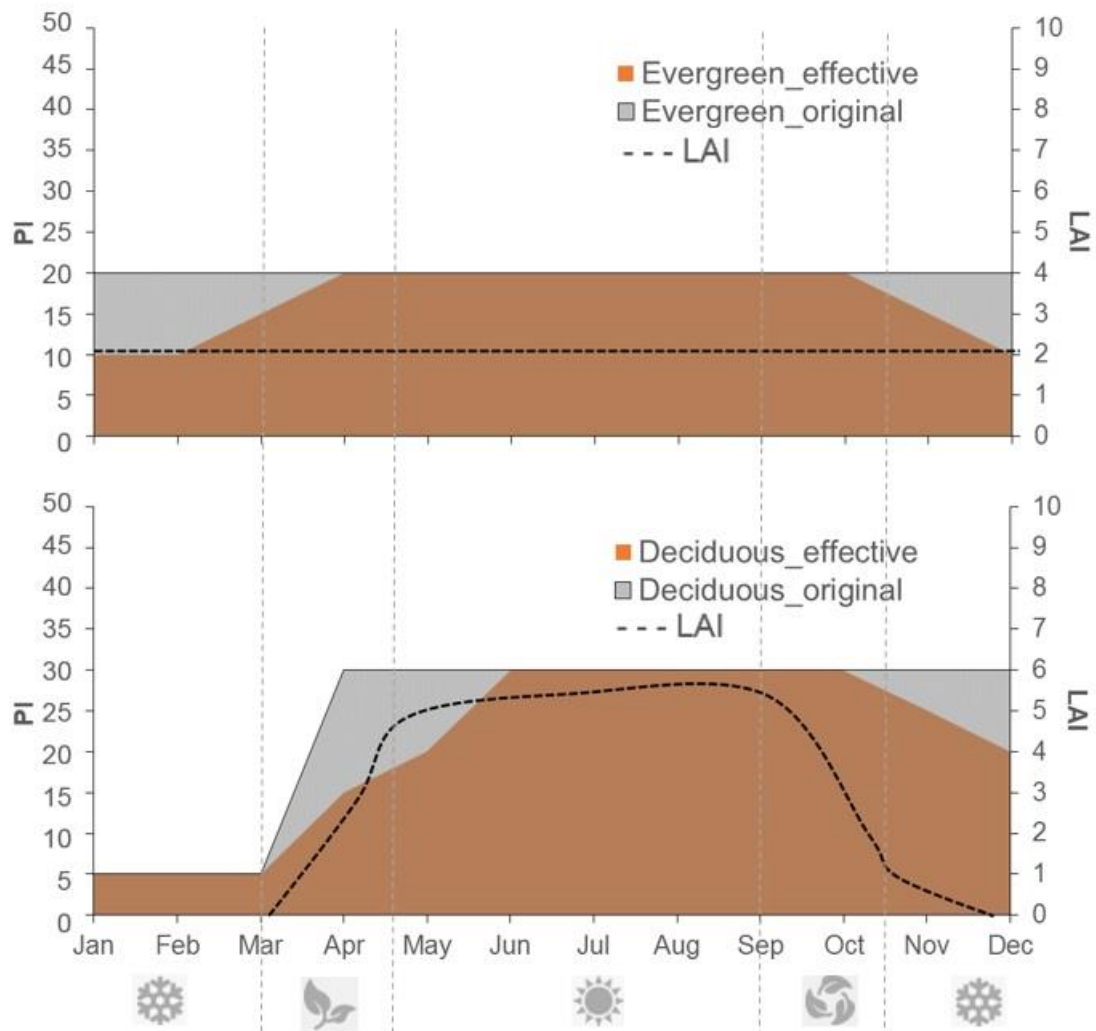
Figure 1

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