# 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

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

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

A considerable amount of research efforts have gone into assessing the effects of air pollution on roadside vegetation (Lau, 2001; Truscott et al., 2005; Wagh et al., 2006; Bignal et al., 2008) and conversely on their role in mitigating air pollution (Yang, 2005; Nowak et al., 2006; McDonald et al., 2007; Tiwary et al., 2009). Evaluation of the net effect of increased vegetation on the urban air quality in the local-to-neighbourhood scale street environment has been a central theme of recent research studies (Salmond et al., 2013; Gromke and Blocken, 2015). Increased traffic-generated N-emissions have been associated with accelerated growth of some 'lower plant' species (e.g. bryophytes) along streets, mainly owing to fertilisation effects of the scavenged $NO_x$, $HNO_2$ and/or $NH_3$ emissions on their surfaces (Bignal et al., 2008). Certain tree species have been earmarked for plantations along the roads as bio-monitors for vehicle emissions (Moreno et al., 2003; Hofman and Samson, 2014). However, despite some generalised modelling studies, there is still much to be learned about the characteristics and ecophysiology of different types of urban vegetation and their interaction with the street environment (Calfapietra et al., 2015). This indicates an urgent need to improve our understanding of the environmental responses of the vegetation species used before decisions are made about streetscape species selection. Street tree good practice guides have been developed - outlining the design criteria for street plantations, choice of suitable tree species and maintenance requirements - with increasing emphasis on planting smaller tree species as street trees because they fit better into narrow pavements and are easier to manage (Pauleit, 2003; Britt and Johnston 2008; Armson et al., 2013b; Forest Research, 2014). A generalised prescription for suitable streetscape vegetation species and genotypes include – tree life span; required growth space and adaptability to the local environment; tree functionality (pollution/noise attenuation, cooling, flood risk aversion, storm water reduction, etc.); cost of propagation, establishment and management; aesthetics; stress and drought tolerance; potential allergenicity of species (Sæbø et al., 2005; Vlachokostas et al., 2014).

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

## 2. Development of performance index

Understanding and improving the environmental performance of street/roadside vegetation comprehensively (trees, shrubs, forbs etc.) has motivated the development of index-based frameworks. Several researchers have expended efforts towards developing performance indices for specific application of urban trees – for example, towards greenbelt development for pollution alleviation (Prajapati and Tripathi, 2008); for reducing of traffic-generated noise (Pathak et al., 2011); for more comprehensive evaluation of their ecosystem services and goods from urban forests (Dobbs et al., 2011; Kenney et al., 2011), etc. A recent study developed a decision-making scheme for benchmarking/prioritising tree species in urban environments using a framework which combines two multi-criteria methods to provide an optimal ranking. The set of multiple criteria include tree life span, required growth space, planting capability in built environment, aesthetics, tolerance, pollution attenuation, adaptation to local climate, crown density, cost, and potential allergenicity of species (Vlachokostas et al., 2014). However, their study does not appear to address the issues pertaining to street environment and has not considered biogenic emissions (BVOCs) from vegetation *per se*.

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

### *2.1 Pollution flux potential*

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

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

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

Both $P_{dep}$ and $P_{emit}$ (expressed as kg yr$^{-1}$) can be either literature-derived (based on leaf-level activity values of pollutant depositions and emissions) or directly acquired from field campaigns. $P_{dep}$ includes dry deposition of the following five air pollutants - ozone ($O_3$), sulfur dioxide ($SO_2$), nitrogen dioxide ($NO_2$), carbon monoxide (CO), and particulate matter less than 10µm (PM10). $P_{emit}$ includes emissions of isoprene, monoterpenes and other BVOCs (USDA, 2008). The quantification of pollen emissions has not been included as part of $P_{emit}$ owing to their narrow window of influence on an annual basis.

*2.2 Carbon sequestration potential*

Vegetation sequester atmospheric carbon in the form of biomass and their sequestration potentials vary widely between species depending on their phenology and growth characteristics (Davies et al., 2011). Recent evaluations of carbon storage and sequestration by urban trees have been reported (Escobedo et al., 2010; Zhao et al., 2010; Foster et al., 2011; Nowak et al., 2013). It is worth noting that urban forests are estimated to store approximately 50% less carbon than natural forests – possibly due to the younger age of trees in urban areas (Nowak & Crane, 2002; McPherson, 2010; Zhao et al., 2010). However, a study by Nowak & Crane (2002) found rates of carbon sequestration decrease as a tree matures so young trees in urban areas could be considered beneficial. The carbon sequestration potential (CSP) takes into account the capacity of the entire plant to store carbon within woody, long-lasting tissues considering that fine roots and litter have a relatively fast turnover. The carbon sequestered in the soil has been omitted from these estimates owing to inadequate information to date about the carbon fluxes in urban soils for a diverse range of street tree plantations and their disturbances during road works, soil amendments, etc. Various approaches have been adopted to determine the CSP of tree species, one of which is empirical equations, similar to the one shown in (**Eq. [2]**, expressed as kg $yr^{-1}$), based on field scale studies in terms of the total biomass carbon content (Northup et al., 2005).

$$CSP = AGB \times TBCF \times C \qquad [2]$$

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

### *2.3 Thermal Comfort Potential*

Street trees have been found effective in mitigating the effects of heat and drought at highly sealed urban sites, can have a substantial cooling effect on the urban air temperature (Leuzinger et al., 2010; Gillner et al., 2015), and have been reported to reduce cooling energy demand by 20% (Akbari et al. (2001). Microclimate modelling of the cooling effect of street trees in their immediate vicinity show strong dependence on three parameters - the built form geometry (building height and street width), the canopy coverage level and planting density – with negligible influence of other species characteristics, such as leaf size and other plant physiological parameters (Shashua-Bar et al., 2010a). It is noteworthy, for any tree coverage level the cooling effect of street trees strongly vary with available open space - deeper canyons (i.e. building height > street width) tend to reduce the tree cooling effect, requiring trees with fastigiated crowns planted in those sites, mainly for shading and thermal comfort in the noon hours; shallow canyons (i.e. street width > building height) on the other hand enhance the cooling effect, requiring plantation of broad-leaf trees in minimum planting intervals. Further, more drought-tolerant and slow-growing trees have been found to reduce radiation less than faster-growing species, hence providing less evapo-transpirational cooling owing to their less dense canopies (Armson et al., 2013b). Typically on a warm sunny day passive cooling offered by a street tree (quantified as reduction in surface temperature and thermal loads) has been reported to bear strong positive correlation with its canopy projection area and LAI (Armson et al., 2013b; Gillner et al., 2015). These two tree characteristics have been used to parameterise its indicative Thermal Comfort Potential (TCP) as shown in **Eq. [3]**

$$TCP \sim CanopyArea \times LAI \qquad [3]$$

*2.4 Noise Attenuation Potential*

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

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

*2.5 Biomass Energy Potential*

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

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

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

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

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

*2.6 Environmental Stress Tolerance*

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

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

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

*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]**).

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

## 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

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

*<place Table 1 somewhere here>*

*3.2 Data collection and analysis*

All sampling was performed within 100 m of the verge of the main road since literature evidence suggests strongest effects of traffic-generated pollutants in the first 50-100 m from road (Bignal et al., 2008), with particulates decreasing in concentration more rapidly than gaseous constituents, and gases with a high deposition velocity (such as $HNO_2$ and $NH_3$) decreasing more rapidly than those with a lower deposition velocity (such as NO and $NO_2$) (Truscott et al., 2005). The earmarked traits for the vegetation species were evaluated using a combination of experiments and literature survey for acquiring the underlying datasets, as described below and summarised in **Table 2**.

*3.2.1 Pollution Flux Potential*

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

*3.2.2 Carbon Sequestration Potential*

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

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

*3.2.3 Thermal Comfort Potential*

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

*3.2.4 Noise Attenuation Potential*

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

*3.2.5 Biomass Energy Potential*

For estimating the BEPs, the required constituent chemical composition of woody biofuels - *C, H, O, N, S* and *Ash* (see **Section 2.5**) of the selected species typically representative of temperate climes in Europe and North America were acquired from literature survey (**Table 2**) (Obernberger et al., 2005; AIEL, 2008; Tumuluru et al., 2011). Those species which have not been exclusively listed in the literature were approximated as typical values of the following categories – virgin wood thinning (coniferous or deciduous wood/ logging residues), wood chips, short rotation coppice pruning – provided in AIEL (2008).

### *3.2.6 Environmental Stress Tolerance*

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

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

*<place Table 2 somewhere here>*

## 4. Results and Discussion

### *4.1. Performance index*

The Performance Index (PI) framework was successfully applied to the species included in the case study, demonstrating its capabilities for conducting a comprehensive evaluation of street trees. For each species first the values of the seven traits were quantified through the proposed methodology and then they were harmonised using the gradation scheme (**Table A.1**) to obtain their corresponding PI scores (**Table 3**). Despite variations in constituent traits, a number of species attain similar PI score (mostly in 13-17 range), primarily owing to different combinations of individual gradations for the seven traits considered. This is crucial for developing a sustainable streetscape green infrastructure and reflects the strength of the PI approach in incorporating multi-dimensional attributes of the species in ensuring their worthiness of streetscaping. It is worth mentioning that the pollution flux 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 the constituent traits of the PI could be over- or under-estimating the resultant values. Albeit, the inventory generated from the i-Tree Eco model is the most extensive publicly-available dataset thus far (USDA, 2008), enabling screening level assessments to explore the trends without excessive dependence on the experimental resources. Nevertheless, more ambitious assessments of streetscape should follow representative evaluation of the constituent traits using the PI methodology. This could also involve detailed analyses of site-specific samples corresponding to the study area's tree species, climate, seasonality, management practice, etc. It is also noteworthy that the units of the traits are to be strictly adhered to for consistency in allocation of representative grading score (**Table A.2**), failing which will yield an anomalous PI score. The CSP estimations are based on empirical equations specific to Europe for the majority of the species, however, a small number of species with no Europe-specific information have been approximated using general equations. As such, this introduces some uncertainty in the calculations, but for the added benefit of allowing a much broader screening assessment of popular street vegetation this has been accepted as an affordable trade-off. The derivations used for estimating TCP and NAP are purely indicative of the trends, based on their characterising parameters as reported in the recent literature.

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

*<place Figure 1 somewhere here>*

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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**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 (*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]<br>Leaf area index (LAI)[a] | Inventoried literature data | USDA (2008) |
| **Noise Attenuation Potential (NAP)**† | Avg. leaf biomass (kg) [a]<br>Canopy area ($m^2$)[a]<br>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: $$\frac{(E_0 - E_s - E_t)*V}{W \times 100} \times 100$$ 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 | TRAITS-VALUES | | | | | | | TRAITS-GRADES | | | | | | | | PI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Common Name | 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 |

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**Figure 1**

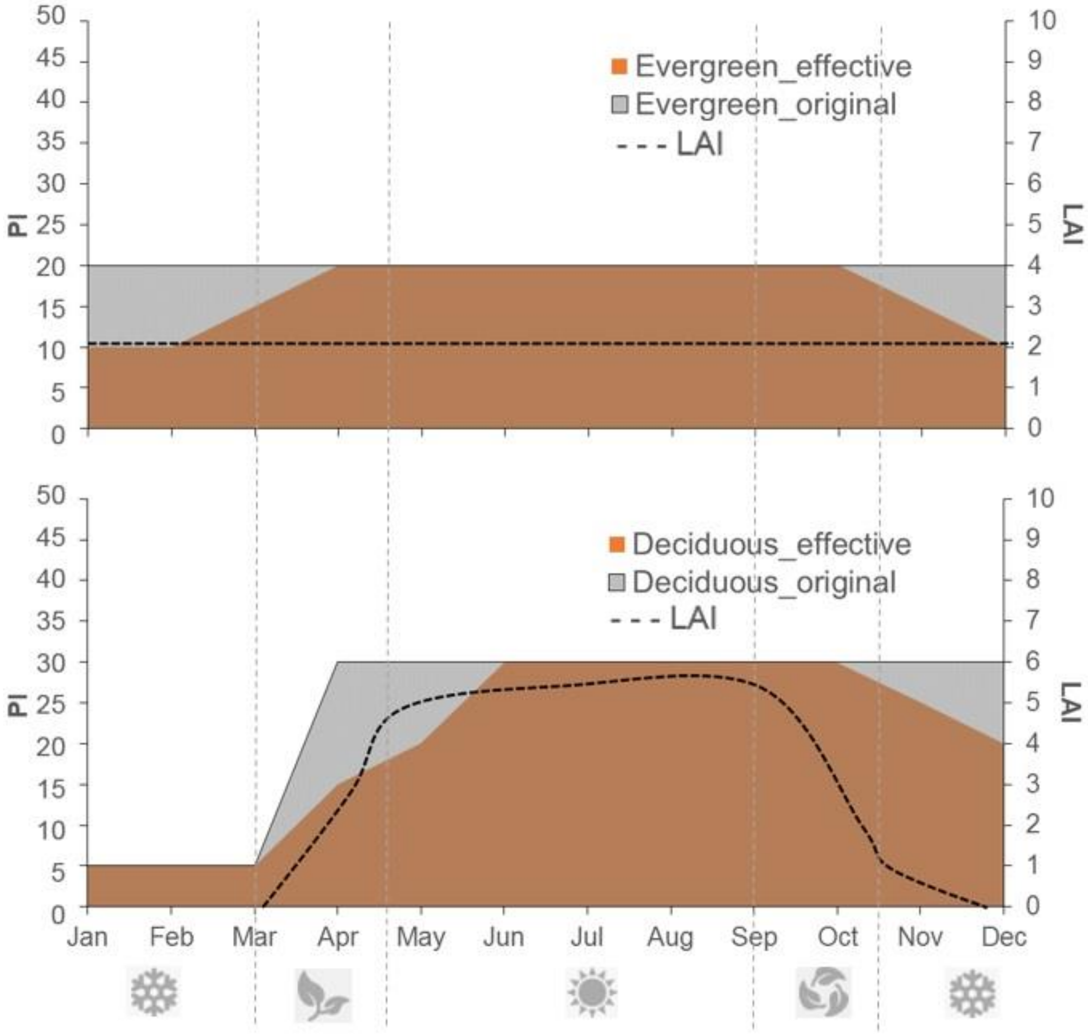


**Figure 1. Schematic representation of the hypothetical $PI_{Effective}$ (foliage-cover weighted PI) of vegetation over four seasons, upper panel: evergreen; lower panel: deciduous [note: dotted line depicts LAI on the secondary y-axis, which is considered static for evergreen but variable over the 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 |
|---|---|---|
| *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. $2.7\times10^{-9}$ | 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 $stand^{-1}$.