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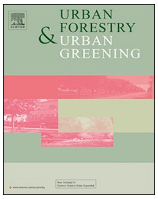

Urban hedges: A review of plant species and cultivars for ecosystem service delivery in north-west Europe

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ABSTRACT

Urban hedges provide a number of important ecosystem services (ESs) including microclimate alteration, flood and pollution mitigation, and biodiversity provision, along with some disservices (DSs, e.g. invasiveness, allergenicity). However, hedge plant species differ in their capacity to promote different services, so it is important that the decision to plant hedges is evidence-based. The objectives of this study were thus to (i) to review the role of urban hedges within NW Europe; (ii) review the available literature detailing the ESs and DSs provided by different plant species and cultivars when used as hedge plants; (iii) identify where there is a lack of evidence for certain species or ESs/DSs; and (iv) develop a starting point for a discussion about appropriate species/cultivar selection to deliver *multiple* ESs, and avoid DSs.

Many studies consider biodiversity and air quality ESs. There are significant gaps in the literature relating to rainfall mitigation/flood protection, but also CO_2 sequestration, allergenicity and human psychological well-being impact of different species. Additionally, for noise and pollution mitigation studies, a range of methodologies and units are used, making comparisons between hedge species difficult/impossible.

A number of common hedge species demonstrated high levels of ESs delivery, including *Fagus sylvatica*, *Crataegus monogyna*, *Ilex aquifolium* and *Rosa rugosa*. No species surveyed had an entirely negative association with ESs, and most provide at least some benefits in supporting ESs provision (e.g. *Viburnum tinus, Laurus nobilis*). We created a matrix, in a table form, linking plant species, key plant traits and ESs/DSs, which should make it easier for professionals to choose species best suited to provide multiple benefits, whilst minimising the drawbacks. Our review suggests that the relative contribution of urban hedges to ESs delivery may be under-valued currently, and calls for more research.

1. Introduction

The role of green infrastructure (GI) in providing urban ecosystem services (ESs) is increasingly recognised (e.g. Oberndorfer et al., 2007; Livesley et al., 2016; Cameron and Blanuša, 2016) and beginning to influence policy (e.g. EU biodiversity strategy, 2011 http://ec.europa.eu/environment/nature/ecosystems/index_en.htm; GLA, 2017). Studies involving different forms of green infrastructure (GI) (street trees, hedges, green roofs, parks etc.) have identified how plants contribute to a multitude of *individual* ESs. These services include environmental considerations such as mitigation of surface and air temperatures (Alexandri and Jones, 2008; Shashua-Bar et al., 2009; Blanusa et al., 2013; Cameron et al., 2014), air quality and pollution mitigation (Rowe, 2011; Tallis et al., 2011; Abhijith et al., 2017), rainfall capture and retention (Czemiel Berndtsson, 2010; Berland et al., 2017), noise abatement (Van Renterghem et al., 2014), carbon sequestration (Gratani and Varone, 2013), phytoremediation of soils and water (Zhang et al., 2007) and biodiversity provision (Davies et al., 2009; Dover, 2015; O'Sullivan et al., 2017). Moreover, GI contributes to human health and well-being (Grahn and Stigsdotter, 2010; Cameron et al., 2012; Shanahan et al., 2015) and cultural services that include education (Hodson and Sander, 2017), recreational opportunities (Grunewald et al., 2017), social capital (Holtan et al., 2015; Bogar and Beyer, 2016) and economic development (Nesbitt et al., 2017).

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Deriving links between individual service provision and particular plant species becomes important in this context – for example what plant species (or cultivar) do you use to best decontaminate polluted soil or provide best flood risk alleviation? As data accumulates on ESs, however, opportunities arise to identify the *multiple* services that certain species may provide. Conversely, a better understanding of any disadvantages (disservices - DSs) associated with plant species also ensures that inappropriate plants are not used in certain locations. By beginning to catalogue these multiple services (and any disservices), practitioners such as landscape architects and urban planners are better placed to make informed choices about the plants used in urban design, as well as justifying greater deployment of GI based on its enhanced functionality, and ability to meet a wide range of societal needs. Despite these objectives, the majority of urban planting schemes are still determined in practice by aesthetics, cost and the suitability of plants for any given location (e.g. what is resilient enough to survive). In private gardens too, plant choice is largely driven by aesthetic appeal, although in recent years concerns over reductions in invertebrate biodiversity (mainly Lepidoptera and Hymenoptera) have resulted in promotional campaigns to use garden plants for the specific purpose of increasing nectar and pollen availability to insects (e.g. Plants for Pollinators, RHS, UK https://www.rhs.org.uk/science/conservation-biodiversity/wildlife/plants-for-pollinators). In this paper we argue that through better documentation of the services provided by different plant species, more nuanced urban design is possible and that this will maximise the benefits provided by GI. The paper uses one particular typology of GI – namely that of urban hedges, to demonstrate how plant composition can affect the range of ESs provided.

A small number of recent studies (Tiwary et al., 2016; Dusza et al., 2017; O'Sullivan et al., 2017) have introduced the concept of a 'performance index' for selected urban species (predominantly trees), which is linked to the provision of *multiple* ESs. Species may even be ranked based on their ESs profiles, with some researchers also 'factoring-in' resilience to environmental stress (Tiwary et al., 2016; O'Sullivan et al., 2017). We adopt here a comparative approach, albeit acknowledging that some species have received very little research attention to date.

Green infrastructure represents a wide range of plant types (trees, shrubs, herbaceous perennials, annual bedding plants etc.) and no detailed single review can comprehensively cover all these types against their multiple ESs. As such, the focus of this review is the '*urban hedge*': one of the more common forms of urban GI typology, and due to its typical scale and common management approaches, one that offers a degree of valid comparison between plant species. Hedges are particularly important in an urban context, due to city densification and where there may be pressure on space for parks and large stature trees in future (Haaland and van den Bosch, 2015). Hedges in comparison take up less space, at least in terms of width, and along with green walls and roofs may be more critical in future in providing cities with effective green infrastructure (particularly in the light of recent re-evaluation of the role of trees in the urban context, Pugh et al., 2012; Abhijith and Kumar, 2019). Local authorities are now keen to provide multiple services from managed green space in an attempt to meet key criteria on air quality, biodiversity and flood avoidance, as well as deliver social and recreational benefits for the public (Dunn, 2010). Hedges have a key role to play in this, especially as their relatively compact nature may suit higher-density housing developments more readily than many other forms of GI. Despite this, there is limited documentation about the relative value of urban hedges, and particularly how plant species choice within a hedge affects its functionality in terms of ESs delivery. Thus, the objective here is to identify the multiple ESs (and DSs) associated with different hedge plant species, so that this informs future species/cultivar selection and thereby optimise the benefits derived from urban hedges.

For this review we define an urban hedge as a row of closely-planted shrubs or trees, along the edge of a garden, road, park, and urban developments, which is actively managed (pruned or trimmed) to increase the branch density and create a semi-permeable barrier of stems and leaves (Fig. 1). As growth is constrained by regular pruning, when trained as a hedge many trees and shrub species fail to reach their natural height and their inherent form can be radically altered – for example by conforming to regular geometrical shapes for example as rectangular topiary. Although urban hedges can be composed of more than one plant species, the majority consist of a single species (for uniformity of design and consistency of management) (Van Renterghem et al., 2014). It is this monoculture within a single hedge that allows valid comparison between hedges of different taxa (i.e. species or cultivars). We also differentiate and largely exclude from the review rural hedges (hedgerows), which are primarily planted to constrain livestock or protect crops from wind, only considering information on rural hedges that readily transfers across to an urban context, for example species appropriate for wildlife or able to reduce rainfall runoff.

The paper first provides a brief overview of the role of urban hedges. It then utilises a aggregative systematic review process to identify which plant species / cultivars can provide *multiple* ESs, what our level of understanding of these services is when delivered *via* a hedge system, and where the gaps in knowledge lie. The study restricts itself to plant species associated with use in north-west Europe, due to their relevance for the authors' geographical area of activity; it includes plant species commonly grown, but not necessarily native to this region.

The objectives of this study were to (i) to briefly review the role of urban hedges within NW Europe; (ii) review the available literature detailing the ESs and DSs provided by different plant species and cultivars when used as hedge plants ; (iii) identify where there is a lack of evidence for certain species or ESs/DSs; and (iv) develop a starting point for a discussion about appropriate species/cultivar selection to deliver *multiple* ESs, and avoid DSs. We see this review as an *evolving document*, beginning to collate in one place information on documented benefits, challenges and unknowns by urban hedge plants.

2. Methodology

2.1. Identifying common urban hedge plant species

At the centre of our interest were *plant species* commonly used in *urban hedges* within NW Europe. Species were selected using three complementary approaches: by reviewing online nursery catalogues (hedging specialists in western European countries), using data obtained from the Royal Horticultural Society (RHS) Gardening Advice service and consulting UK nursery business / contractors through personal contacts (for their opinions on the most popular lines).

The online catalogues of six major UK hedge producers and suppliers were reviewed in June 2017 and again in March 2019 (Buckingham Nurseries, Ashridge Nurseries, Hopes Grove Nurseries, Hedge nursery and Hedges Direct), along with those from two Dutch (Netplant.nl, Jan Nieuwsteeg), two German (Lappen Tree Nurseries, Bruns.de) and one Belgian producer (Van Pelt). To select hedges within catalogues the search terms 'urban hedge' or 'garden hedge' were placed in the search engine 'Google'. NB a number of suppliers specifically differentiated between species for rural field boundary use and those for garden/urban use, as well as provided special selections based on other criteria 'rapid-growing' 'coastal exposed sites' etc. There was a significant overlap between all catalogues in species on offer for garden / urban situations; those mentioned in all catalogues made it to the selected shortlist (e.g. *Ilex, Taxus, Thuja, Ligustrum, Berberis, Fagus, Carpinus, Prunus* species). Species predominantly used in rural locations (within hedgerows or as wind-breaks, and specifically omitted from the garden/urban sub-sections within website catalogues), were excluded, for example *Populus* species.

The selected species include the 'top 25' of the most enquired about hedges received *via* RHS horticultural advisory service (which receives over 60k gardening-related enquiries annually and serves a membership base of 500,000+ gardeners in the UK, providing a representative

Fig. 1. Examples of hedges in various urban and suburban scenarios, creating a boundary between a street and a property (images - T. Blanusa).

insight of what is present in UK gardens). These species, encouragingly, included all the ones already identified in the nursery catalogues. We checked that these 25 taxa were commonly used in the landscape plant trade by contacting two further nurseries and two landscape contractors (who wish to remain anonymous), who verified these plants were ubiquitous as hedging material. However, a number of additional taxa (18) were additionally mentioned by these professionals as being widely used / becoming more popular as hedge plants and these were added to the shortlist for evaluation.

2.2. *Review of academic literature*

The role of urban hedges was reviewed using the databases Google Scholar and Science Direct. These databases were selected due to their comprehensive coverage of the academic research: database Google Scholar for example, indexes academic information from various other online web resources, allowing further links to track specific papers / books (Haddaway et al., 2017). Information used was restricted to peer-reviewed papers and books / book chapters published in English language. Key-word searches were conducted in June-July 2017 and in March 2019, with no lower limit and up to the dates when search was carried out.

2.2.1. *Mining general hedges information*

Initial searches used key-words including ‘urban-hedge’ or ‘garden-hedge’; these terms were then further refined by additional words - ‘history’ ‘attitude’ ‘function’ ‘ecosystem service’, ‘dis-service’/ ’disservice’ and ‘benefits’. A combined search for example ‘garden-hedge’ and ‘history’ uncovered 786 citations, but only 10% of those actually related to factual information about garden hedges.

2.2.2. *Identifying target ecosystem services/disservices*

Once this initial review was complete, the process was repeated, but with each species/cultivar identified from the selected list (see above) inserted along with one of the following terms ‘ecosystem service’, ‘dis-service’/’disservice’ or ‘benefits’. Searches were conducted with both botanical/Latin and common plant names. This process allowed key ecosystem services / disservices to be identified (Tables 1 and 2). Additionally, services framework discussed by (Pataki et al., 2011) came up repeatedly in our searches, and due to the quality of their review, we used it as a sound-check of our selection.

2.2.3. *Fine-tuning species-related information*

To check for the delivery of ESs/DSs against each species we used these individual terms (e.g. ‘cooling’, ‘micro-climate’, ‘well-being’,’ allergen’, etc., see Tables 1 and 2) in combination with each of the selected plant species (using both Latin and common names) in an attempt to yield further papers / books. Finally, to make sure that each species was thoroughly examined, we searched using just botanical/ Latin and common names alone, and then checked if any of the recovered references addressed one of our focus ESs/DSs. For each search term/s we observed at least the first 100 hits (10 pages), but after that stopped searching when > 80% of the hits on each page were clearly of little relevance, for example when two terms were not linked in any way for example "*Larger conductors needed due to inferior cooling conditions* … and … *So, a 10000-ton freighter, MV Photinia, was chartered and specially fitted with cable-laying…*".

To decide which of the references recovered by using these keyword searches should be included in the review, we performed the analysis of titles, keywords and abstracts. For each paper meeting the criteria (i.e. having as a subject one of our interest species, and some aspect of the target ESs/DSs), it was documented whether the plant had been used within a hedge (or similar, e.g. as a row of containerised plants), or alternatively as a 'free-standing' specimen. This approach was adopted as there is a much larger volume of information available on species used as trees/shrubs in an urban context, rather than as hedges. As long as this species can be also managed and grown as a hedge, we chose to extrapolate, with caution, potential services it might be able to provide as a hedge too. This information was then used to comment of the suitability of the species, when used in a hedge (and where some characteristics may be different – height, density of branches, propensity to flower). The services / disservices were linked to plant species and cultivars (Table 3). Comments within Table 3 provide information on the characteristics of the plant species (or cultivar, where appropriate) as a hedge, and interpretation of its potential benefits/drawbacks. This Table provides the basis for an evolving, future decision-support matrix to aid practitioners in the selection of hedge species in line with ESs/DSs capacity.

Throughout the review we use the term 'traits' which, for the purposes of this review, encompasses structural and anatomical ones (e.g. presence and absence of leaf hairs, leaf size and shape etc.) as well as functional ones (e.g. rate of evapo-transpiration, CO_2 assimilation rate).

3. Results and discussion

3.1. Review process

The initial review yielded 88 papers/books worthy of further consideration and when analysed further these identified 11 ecosystem services and 5 disservices, associated with urban hedges (Tables 1 and 2).

The second review process linking ESs/DSs to plant species or cultivars utilised 139 papers (Table 3), covering 105 different journals and books. Most of the cited papers belonged to disciplines of plant biology, horticulture, forestry, agriculture, (urban) ecology, landscape architecture and environmental science. Papers covered the period 1972–2019, with 2/3 of the references being published since 2008 and geographically predominantly originating in Europe and North-America (with a small but representative number – particularly on pollution – from China).

The databases' search revealed that for some species or services there is significant volume of high quality data available, so can that confident conclusions about species' contribution can be made; for other species data is partial or non-existent. This contributed to the content in Table 3 varying in the extent of literature cover for different species.

3.2. Urban hedges

Motivations to plant urban hedges vary, but they are usually introduced to mark boundaries between properties, or public space and private space. They are largely associated with enclosing private gardens, but hedges may also be used in the public domain (e.g. perimeters of parks, along street corridors and around municipal or industrial buildings). Hedges are a ubiquitous feature within urban landscapes of NW Europe and in generic terms afford a number of frontline ES including privacy, security against intrusion, screening-off visual intrusions such as major roads, railway lines and unsightly industrial developments, providing shelter, pollution and noise mitigation, rainwater capture (flood protection) and habitat for wildlife (Varshney and Mitra, 1993) (Table 1). Hedges have been used historically to enclose gardens within castles and monasteries (Aben and De Wit, 1999) or and provide 'aesthetics within the landscape' for example the parterres of Versailles, France (Baridon, 2008). In the 19th and 20th century there were closely associated with the development of suburban gardens (Barker, 2012), as residential housing moved away from the city centre, and garden ownership became more common.

Table 1
List of ecosystem services (ESs) identified from the review, along with the additional search terms used to recover the information on the services (provided in brackets, in italics). Where there is no information in brackets, the search term was the same as the service in question, and/or the information was deduced indirectly from searches of botanical or common name.

Air quality improvement (air quality, air quality improve*)
Biodiversity/value to wildlife including pollination support (biodiversity, pollinat*, wildlife)
Carbon sequestration (carbon)
Human health benefits (health, well-being)
Noise mitigation (noise)
Phytoremediation of soil pollutants (soil pollutants, heavy metal*)
Thermal benefits/cooling and insulating potential / wind speed reduction (cooling, insulat*, thermal benefit*)
Water management/rainfall capture and flood risk reduction (rainfall mitigation, flood*, water management)
Security – due to being impenetrable due to thorns or spines
Seclusion / privacy
Screening unsightly objects or views

Table 2
List of ecosystem disservices (DSs) identified from the review, along with the additional search terms used to recover the information on the disservices (provided in brackets, in italics). Where there is no information in brackets, the search term was the same as the disservice in question, and/or the information was deduced indirectly from searches of botanical or common name.

Allergenicity
Air quality reduction *(air quality, VOCs⁺, BVOCs⁺)* Invasiveness *(invasive*)* Excessive shading Labour intensive for example need for frequent pruning *(pruning)*

⁺ (B)VOCs- (biogenic) volatile organic compounds.

There appears little data documenting the total area/length of urban hedges, but the fact that green space can account for 20–49% (Anon, 2017) and private gardens 15–25% of the total area of UK towns/cities (Gaston et al., 2005; Mathieu et al., 2007), their extent is likely to be significant. They may represent an under-appreciated asset, however, and be a victim of changing urban trends. For example, there has been a recent decline in vegetative cover within gardens, with almost 40% of UK front gardens now having ≤25% green cover (Anon, 2016). Moreover, garden hedges in general can have a poor reputation, but this corresponds to problems with one species predominantly, *Cupressus* × *leylandii*, which due to its vigour of growth can rapidly shade out gardens and cause disputes between neighbours (Evans, 2002). The review highlighted a number of other disservices, however, associated with urban hedges (Table 2).

3.3. Species choice and attributes

In terms of papers identifying ESs/DSs associated with particular plant taxa, those focussing specifically on hedge systems were in the minority, i.e. most information relates to individual trees or shrubs. A high proportion of studies focused on some aspect of pollution, air or soil quality, whilst only a few considered C sequestration, allergenicity and thermal regulation (Table 3). Despite the wealth of new research on health and social benefits linked with GI, studies linking these with specific plant species were rare. Other cultural services such as

Table 3

Plant taxa and ecosystem services / disservices as cited from the literature, either when research conducted in the form of a hedge (Hedge) or from individual plants and information translated to application within a hedge context. Key - AQ = air quality, Bio = biodiversity, CS = carbon sequestration, HM = heavy metals, HW-B = human health and well-being, Inv = potentially invasive in some locations, NM = noise mitigation, Pution = pollution, Pnator = pollinator, Wat = water management.

Species	Hedge	Other research translated to hedge situation	Comments
Amelanchier lamarckii		Bio & Inv (Halford et al., 2014)	Berries provide food for birds, even where the species is non-native. Invasive (Halford et al., 2014).
Berberis darwinii		Bio & Inv (Williams, 2006)	Low hedges with berries that are attractive to birds. Invasive e.g. in New Zealand (Williams, 2006).
Berberis stenophylla	Security (Brethour et al., 2007)		Thorns on branches make this species suitable as an impenetrable barrier (Brethour et al., 2007).
Berberis thunbergii	Pution - HM (Hu et al., 2014); NM (Mutlu and Onder, 2012; Onder and Kocbeker, 2012)	AQ (Wang et al., 2011); Inv (Silander and Klepeis, 1999)	Bioaccumulation of Cr, but less effective for Pb, Zn and Cd (Hu et al., 2014). Not particularly effective for PM capture (Wang et al., 2011). NM mod. to good, e.g. in combination with other species decreased noise from that of the control by 3.7-6.3 dB depending on combination (Mutlu and Onder, 2012).
Berberis x ottawensis purpurea 'Superba'		Inv (Boyce, 2009)	
Buxus sempervirens	Wat (Kalavrouziotis and Apostolopoulos, 2007); Poor correlation with Pnation (Mach and Potter, 2017); NM (Yang et al., 2012)	AQ (Librando et al., 2002), Bio, (hUallacháin, 2014), Pnation, (Webby, 2004) NM (Yang et al., 2012)	Librando et al., 2002 claim this was one of the best species for retaining PM in their evaluations, although less effective with gaseous pollutants. Useful as a biomonitor for PAH. Tolerates HM (Kalavrouziotis and Apostolopoulos, 2007). Conflicting data on benefit to Pnators – poor (Mach and Potter, 2017) or good (Webby, 2004) – perhaps relating to geographical factors. Larger hedges may offer some opportunities as nesting sites for birds (hUallacháin, 2014). Some NM by 4 dB (Yang et al., 2012).
Camellia japonica	Wat (Camarena-Rangel et al., 2015)	Pution – electromagnetic (Cuinas et al., 2007); Pution (Fang and Ling, 2003); Poor NM (Fang and Ling, 2003); AQ (Liu et al., 2003; Takahashi et al., 2005); Wat (del Socorro Santos-Díaz and Zamora-Pedraza, 2010)	Ability to bioaccumulate fluoride within hydroponic study (Camarena-Rangel et al., 2015). NO$_2$ absorbance / tolerance capacity (Miao et al., 2008; Takahashi et al., 2005) and effective at tolerating atmospheric acids e.g. acid rain (Zhao et al., 2010). May provide some human restoration potential due to mid-deep green leaves and range of flower colours (Kendal et al., 2008), where limited pruning encourages flowers.
Camellia sasanqua		AQ (Omasa et al., 2000); Wat (Zhao et al., 2010)	As above, good tolerance of acidic conditions (pH 3) (Zhao et al., 2010).
Carpinus betulus		AQ (Kardel et al., 2011); Poor for AQ (Cuinica et al., 2015; Frank and Ernst, 2016); Pution - heavy metals, (Zolgharnein et al., 2013); Bio (Helden et al., 2012); Wat (Nordén, 1991); Range of services (Sjöman et al., 2016; Tiwary et al., 2016; O'Sullivan et al., 2017)	Some evidence of PM capture (Kardel et al., 2011) and tolerance/bioaccumulation of Cd from contaminated soils (Zolgharnein et al., 2013). Moderate value for bio (Helden et al., 2012; Sjöman et al., 2016; Tiwary et al., 2016; O'Sullivan et al., 2017) and rainfall capture (Norden 1991). Only larger, less frequently pruned hedges will produce pollen which is allergenic. Allergenicity is increased in this species though by exposure to atmospheric pollutants such as CO, O$_3$, SO$_2$ and NO$_2$ (Cuinica et al., 2015; Frank and Ernst, 2016). Considered useful at providing psychological 'refuge', e.g. used in stress restoration gardens (Stigsdotter and Grahn, 2002).
Chaenomeles japonica		Bio (Madahi and Sahragard, 2012)	Supports Pnation and Aphididae spp. (Madahi and Sahragard, 2012).
Choisya ternata		Pnation (Last and Roberts, 2012); HW-B (Teixeira and Fernandes, 2016)	Flowers have strong attractive perfume and are useful for Pnators; the fact that flowering duration can be prolonged in 'early springs' being a particular merit (Last and Roberts, 2012). Teixeira and Fernandes (2016) claim species/cultivars have restorative effects i.e. promoting feelings of serenity, refuge and sense activation.

(continued on next page)

Table 3 (*continued*)

Species	Hedge	Other research translated to hedge situation	Comments
Corylus avellana	Pution - heavy metals (Huseyinova et al., 2009)	Provisioning (Clark and Nicholas, 2013); Bio (Helden et al., 2012; Rogers et al., 2015); Poor for AQ, (Lorenzoni-Chiesura et al., 2000; Staffolani et al., 2011)	Some effectiveness at absorbing HM and SO_2 (Huseyinova et al., 2009) although not recommended due to its capacity to release allergenic pollen (Lorenzoni-Chiesura et al., 2000; Staffolani et al., 2011). This problem may be limited in a low growing hedge, but so will its capacity to provide nuts for birds, small mammals or humans (Clark and Nicholas, 2013). Age and size is less of an issue for phytophagous insects (Helden et al., 2012; Rogers et al., 2015), which the species is good at supporting.
Cotoneaster spp. various	Bio (Madre et al., 2013)	Thermal regulation (Taylor et al., 2014); Inv (Rejmánek and Richardson, 2013)	C. franchetii proved to be a moderately good species for wall insulation in winter; in that hedges in close proximity to walls reduced thermal flux at night (retained heat close to building), yet allowed the wall to be heated by solar gain during daylight hours (Taylor et al., 2014). This species has been associated with good numbers of insects and other arthropods (Madre et al., 2013). A wide variety of species and cultivars within Cotoneaster have small flowers which are rich in nectar, thus often associated with good numbers of bees and other Pnators (Corbet and Westgarth-Smith, 1992).
Crataegus monogyna	NM (Erdogan and Yazgan, 2009); Bio (Jacobs et al., 2009); Range of services (O'Sullivan et al., 2017)	Bio (Carlos and Gibson, 2010; Helden et al., 2012); poor for HM (Little and Martin, 1972); Pnation (Cayuela et al., 2011; Crowther et al., 2014); Inv (Lafleur et al., 2007)	Mixed reviews on capacity to trap aerial pollutants. Smooth leaves suggested less capacity to retain dust (with Zn, Pb and Cd) than comparator Ulmus (Little and Martin, 1972), but Pyatt and Haywood (1989) had it middle ranking for PM. A popular species for wildlife conservation in rural context and likely to be similar in urban, but only if not trimmed too frequently or too hard. Flowers (nectar / pollen for insects, Cayuela et al., 2011; Crowther et al., 2014), fruit (food for birds / small mammals, Carlos and Gibson, 2010), leaves (Helden et al., 2012) and branch habitat (dense structure and thorns protect birds' nests) are key components for wildlife (Jacobs et al., 2009; O'Sullivan et al., 2017) and excess pruning will undermine the first two aspects. Rogers et al., 2015 ranked it as the 4th most important species for wildlife in an urban context. Has potential too for NM (Erdogan and Yazgan, 2009).
Cupressus macrocarpa			Arguably one of the commercially most commonly available conifers in the UK garden centres at present. No data on it available in the peer-reviewed literature however.
× Cuprocyparis leylandii (Cupressus × leylandii)	Excludes light (Richardson and Rejmánek, 2004; Griggs and Low, 2012)		Fast growing characteristics made this species highly popular in the 1960-2000s as a 'quick screen', but this results in need for frequent pruning (2-3 times a year) and if not pruned results in very large hedges (15 m +). As a result, one of the most complained about plants due to its capacity to 'shade out' neighbour's gardens and deplete soils of water and nutrients (Barker, 2012). A number of legal cases have ensued (Richardson 2002; Griggs and Low, 2012).
Elaeagnus × ebbingei		AQ (Fellet et al., 2016; Mori et al., 2016, 2015); Ption (Mori et al., 2015)	Good at absorbing relatively high concentrations of Cr, Cu, PB (also Fe, Mn) and one of the best for PM (Mori et al., 2015, 2016) and trapping 5- and 6-rings PAHs (Fellet et al., 2016).
Escallonia rubra			There is no peer-reviewed information available, but it is a species worth considering as it is good, practical hedging choice for exposed coastal, windy sites, where not excessively cold.
Euonymus europaeus		Bio (Fung et al., 1988); Inv (Gagliardi and Brand, 2007)	Leaves provide food for herbivores including Aphididae and larvae of certain Lepidoptera (Fung et al., 1988).

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Table 3 (*continued*)

Species	Hedge	Other research translated to hedge situation	Comments
Euonymus japonicus	AQ (Lei et al., 2006); Pution - heavy metals (Mansour, 2014); NM (Mutlu and Onder, 2012)	AQ (Tao et al., 2009; Song et al., 2015; Takahashi et al., 2005); Pution - HM (Zeng et al., 2016); CS (Zou et al., 2014)	Another species with potential as a bio-indicator of Pution (Mansour, 2014) with rel. tolerance of aerial pollutants (e.g. HF, SO_2, NO_2) (Tao et al., 2009; Takahashi et al., 2005; Lei et al., 2006) and HM (Cd, Zeng et al., 2016). Low growing height indicates useful at absorbing PM that is disturbed by traffic at ground level. Tolerated mod. drought stress and still some capacity to absorb aerial gases (Zou et al., 2014). In a mixed planting of species. E. japonicus contributed to a noise reduction level of 3.7-6.3 dB (Mutlu and Onder, 2012).
Fagus sylvatica	NM (Van Renterghem et al., 2014)	AQ (Karnosky, 1981); Pution - HM (Breckle and Kahle, 1992); Bio (Askew, 1980; Horák, 2011); CS (Matyssek et al., 2010)	Shows promising results regarding Pution tolerance. As a free standing tree (Grote et al., 2016) ranked this very high for PM, good for gaseous pollutant capture and tolerance (Karnosky, 1981), and rel. low for self-generated O_3. Some sensitivity was noted with HM: significant leaf area reduction linked with 6 ppm Pb (0.3 ppm Cd) in the leaves (DW), but biomass reduction only with 18 ppm Pb (3.6 ppm Cd) (Breckle and Kahle, 1992). Some rel. minor NM (Van Renterghem et al., 2014), when grown as hedge. Linked with rel. high levels of wood boring (saproxylic) beetle diversity (Horák, 2011), although thinner-stemmed plants within hedges may not be advantageous here. Leaves provide food for a variety of Aphidoidea, Coleoptera, Diptera, Hymenoptera and Lepidoptera spp. (Askew, 1980). Seeds (beech mast) eaten by small mammals and birds, again though production from hedges may be limited. Used as hedge spp. in therapeutic gardens (Stigsdotter and Grahn, 2003), possibly due to attributes such as bright mid –green leaves in summer, and wind-rustling effects of dead leaves in winter.
Forsythia spp. and cultivars		Cooling and recharging soil water holding capacity (Cameron et al., 2006; Jim and Chen, 2009) Bio (Jacob-Remacle, 1989)	Good for solitary bee species (Jacob-Remacle, 1989). Forsythia have been associated with relatively high evapo-transpiration rates, suggesting they have good localised cooling capacity and are able to re-charge a soils water holding capacity after heavy rainfall (Cameron et al., 2006; Jim and Chen, 2009).
Griselinia littoralis		Bio (Ignatieva et al., 2008); NM (Meurk et al., 2013)	Good for biodiversity in its native New Zealand (Ignatieva et al., 2008). Provides effective evergreen screens and shelter belts in coastal regions of NW Europe.
Hebe spp. and cultivars		Biocontrol (Tompkins, 2010); NM (Meurk et al., 2013); Bio (Frankie et al., 2005)	Research in New Zealand (Tompkins, 2010) demonstrates some spp. provide habitat for natural enemies of crop pests. Good at providing nectar (e.g. to bees), even as a non-native plant (Frankie et al., 2005).
Hypericum × hidcoteense 'Hidcote'		Pnation (Switzer and Combes, 2017)	Useful source of nectar and pollen for bumble bees (Switzer and Combes, 2017).
Ilex aquifolium	AQ (Fellet et al., 2016); Pution - heavy metals, (Giorgioni and Quitadamo, 2012)	AQ, CO_2 sequestration (Paoletti, 2009; Hutchings et al., 2012; Ranford and Reiling, 2007a, b); NM (Fang and Ling, 2003); Inv (Zika, 2010)	When estimating the ES value of Edinburgh's Trees, Ilex was ranked second by Hutchings et al. (2012). Has some sensitivity to O_3 exposure (Ranford and Reiling, 2007a, 2007b), although other results suggest it may be useful for adsorbing aerial hydrocarbons. Fang and Ling (2003) indicated that Ilex could contribute to NM when used with other species.

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Species	Hedge	Other research translated to hedge situation	Comments
Laurus nobilis	AQ (Mori et al., 2016, 2015; Fellet et al., 2016); Pution - HM (Giorgioni and Quitadamo, 2012); CS & NM (Gratani and Varone, 2013)	AQ (Christodoulakis, 1993; Noe et al., 2008b; Paoletti, 2009); source of BVOC (Llusia et al., 2012), Pution - HM (Yaşar et al., 2012)	Species with thick evergreen leaves, showing promise to remove PAH (Fellet et al., 2016) and sequester CO_2 (25.4 kg CO_2/month) (Gratani and Varone, 2013; Mori et al., 2015, 2016). Some tolerance (e.g. via stomatal guard cells, Christodoulakis, 1993) to a range of aerial pollutants, and an ability to bioaccumulate HM from the soil. Some evidence that BVOCs may be released, but perhaps only when plant under stress (e.g. drought and high UV) (Paoletti, 2009; Llusia et al., 2012). Noise attenuation potential (14%) (Gratani and Varone, 2013).
Lavandula angustifolia	Bio (Madre et al., 2013)	Pution - HM (Angelova et al., 2015); Bio (Yücel, 2013); HW-B (Li et al., 2012)	Source of nectar/pollen for wide range of Pnators, e.g. Bombus spp. (Garbuzov and Ratnieks, 2014) and Lepidoptera such as Cupido comyntas, Danaus plexippus, Papillo machaon (Yücel, 2013). Lavandula can tolerate soil HM and has phytoremediation potential (Angelova et al., 2015). Considered to have mental health / restorative properties in humans due to hue and aromatics (Li et al., 2012).
Ligustrum ovalifolium	AQ (Gajić et al., 2009; Rucandio et al., 2011); Pution - HM (Mansour, 2014)	AQ (Ashenden et al., 2003; Analojeh et al., 2016); Bio (Debussche and Isenmann, 1990; hUallacháin, 2014); Pollination (Yamada et al., 2014); Inv (Maddox et al., 2010)	Demonstrate mod./high tolerance to HM. Gajić et al. (2009) suggest it has high tolerance to Pb (3.5-4.2 $\mu g\ g^{-1}$from traffic) with active physiological protection mechanisms and could maintain optimal photosynthesis. Some evidence it tolerates mod. levels of Zn, Cr, Cd, Co, Ni and Cu (Mansour, 2014), Sc and V (Rucandio et al., 2011) and Fe, Zn and Cu, 3rd most tolerant out of the species examined by Amini et al. (2011). Effective at trapping dust due to fine branch network, but growth inhibited by excessive deposits on leaves. (Analojeh et al., 2016). Absorption of N compounds also noted, which resulted in higher N/C ratios and increased herbivore injury. When allowed to flower, and fruit (not trimmed too heavily / frequently) then flowers are food source for invertebrates (Yamada et al., 2014) and berries eaten by passerine birds such as Sylvia atricapilla (blackcap) (Debussche and Isenmann, 1990). Semi-evergreen habit provide shelter for small birds and is used as nesting site by various low-nesting species e.g. Erithacus rubecula (robin), Turdus merula (blackbird), Columba palumbus (woodpigeon), hUallacháin, 2014). The morphologically similar L. japonica showed promise in terms of PAH accumulation (Fellet et al., 2016). Associated with 2-3 trimmings per growing season to keep typical dense branch structure.
Lonicera nitida and cultivars		Thermal regulation and NM (Bianco et al., 2017)	Shrub with thin stems and small evergreen leaves; was associated with a green wall system which showed 7 °C cooling in Italy (Bianco et al., 2017).

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Table 3 (*continued*)

Species	Hedge	Other research translated to hedge situation	Comments
Photinia fraseri	AQ (Fellet et al., 2016; Mori et al., 2015), Pution - HM (Giorgioni and Quitadamo, 2012)	AQ (Shu-quan et al., 2010); NM (Fan et al., 2010)	Mori et al., 2015 suggested it was middle ranking with respect to PM absorption, and relatively effective at absorbing Zn from road dust. Conversely it has been cited as rel. sensitive to O_3 (Zhang et al., 2012). The species was noted to be tolerant to PAHs, although not particularly effective at removing them from the air (Fellet et al., 2016). It has moderate to good CO_2 assimilation but retains this better than other species when under drought stress (Mori et al., 2016). Photinia demonstrated growth increments when grown in contaminated soil (from a petrol station) suggesting good tolerance to organic and heavy metal soil pollutants (Giorgioni and Quitadamo, 2012). This species has been linked with NM potential, especially blocking high frequency sound waves (Fan et al., 2010).
Phyllostachys aurea		AQ (Pan and Zheng, 2012); Inv (County, 2016) CS (Song et al., 2011)	A range of bamboo species are used as hedging with P. aurea being an example. Have reputation of being locally invasive through new rhizome growth, the pressure of which can penetrate/crack concrete (County, 2006). Rapid growth though suggest CS potential (Song et al., 2011) and they have PM trapping qualities (Pan and Zheng, 2012).
Prunus laurocerasus	Cooling (Cameron et al., 2014); Thermal insulation (Taylor et al., 2014)	Inv (Thuiller et al., 2008)	Moderate levels of PM and VOC absorbance capacity (Saebo et al 2012; O'Sullivan et al., 2017). Cameron et al. (2014) showed it had good ability to cool in summer (3-6 °C, largely via shade effects) but also insulate infrastructure in winter (Taylor et al., 2014). May be inv. in some locations, and heavy shade impairs ground flora (Thuiller et al., 2008).
Prunus lusitanica		Inv (Randall, 2001)	
Pyracantha coccinea and cultivars		Pution - HM (Akguc et al., 2010); Bioindicator (Hijano et al., 2005); NM (Onder and Kocbeker, 2012); Inv (Richardson and Rejmánek, 2004)	Used as a biomonitor species for HM and SO_2 (Hijano et al., 2005) and seems to have some phytoremediation capacity. Levels within leaves were Cd = 0.36, Pb = 14.9 and Zn = 15.57 $\mu g\ g^{-1}$ dw (Akguc et al., 2010). Some NM when in a mixed plant group. Fruit eaten by birds.
Ribes sanguinium		Bio (Jacob-Remacle, 1989); Inv (Williams, 2006)	Good nectar / pollen source for solitary bee species (Jacob-Remacle, 1989).
Rosa rugosa		AQ (Min and Renqing, 2004; Sæbø et al., 2012); Pution - HM (Calzoni et al., 2007); Inv (Kollmann et al., 2007); Bio (Elleriis et al., 2015)	Min and Renqing (2004) demonstrated this species had tolerance to SO_2 and Pb. Was not found to be particularly effective at removing PM though (Sæbø et al., 2012). Some evidence of tolerating inorganic soil pollutants and accumulating them(Calzoni et al., 2007). Can be invasive (e.g. very Inv on sand dune systems, Kollman et al, 2009). Even in such circumstances has an overall positive effect on bio (Elleriis et al., 2015).
Skimmia japonica		AQ (Sæbø et al., 2012)	Ranked one of the highest plants for PM accumulation (Sæbø et al., 2012)
Symphoricarpos albus		Ption – HM (Łukasik et al., 2002); Bio (Kollár and Hrubík, 2009); Inv (Richardson and Rejmánek, 2004)	Some tolerance to HM (Łukasik et al., 2002) and urban conditions in general (Flint, 1985), and useful for biodiversity e.g. leaf mining insects (Kollár and Hrubík, 2009). Has invasive tendencies in optimal environments (Richardson and Rejmánek, 2004).

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Species	Hedge	Other research translated to hedge situation	Comments
Taxus baccata	AQ (O'Sullivan et al., 2017); Bio (O'Sullivan et al., 2017); NM Van Renterghem et al., 2014)	AQ Noe et al., 2008a,2008b, Paoletti, 2009, (Samecka-Cymerman et al., 2011; Nováková and Neustupa, 2015; Przybysz et al., 2014; Sæbø et al., 2012); Bio (García and Martínez, 2012)	AQ – middle ranking species (Przybysz et al., 2014; O'Sullivan et al., 2017) in terms of PM accumulation; was better choice for roadsides in drier areas (Przybysz et al., 2014). Seen as a useful bioindicator for AQ (Samecka-Cymerman et al., 2011; Nováková and Neustupa, 2015). Evidence of absorbing O_3 (Paoletti, 2009). Stabilises soil from wind / water erosion (Hanus-Fajerska and Ciarkowska, 2010). Bio, useful for frugivore birds such as Turdus spp. (García and Martínez, 2012), and nesting site, but rel. poor for insect diversity (Kennedy and Southwood, 1984). Some NM (traffic) Van Renterghem et al. (2014). Most parts of the plant are poisonous. Traditionally been a problem as hedging around livestock, but similar implications for domestic animals / children in domestic situation. Linked to the emission of VOCs (Paoletti, 2009), but low (monoterpenes) compared to other evergreens (Noe et al., 2008a, 2008b). Not optimum for insects (Kennedy and Southwood, 1984). Deemed to have poor tolerance to HM in soil (Hanus-Fajerska and Ciarkowska, 2010).
Thuja plicata		Wat (Keim et al., 2006; Asadian and Weiler, 2009); CS (O'Brien et al., 2012)	Dense canopy of fine leaves with individual trees linked to effective rain capture and detention (Keim et al., 2006; Asadian and Weiler, 2009). Similar, albeit smaller scale interventions expected with hedge plants. Dense canopy provides secure nesting habitat for passerine birds (Carbó-Ramírez and Zuria, 2011). Despite being grown as a hedge, flowers still likely to form, so may be a source of allergenic pollen in urban areas. Deemed not useful for improving AQ (Cariñanos and Casares-Porcel, 2011). Species has allergenic properties (Guerin et al., 1996).
Viburnum tinus	AQ (Mori et al., 2016); Pution - HM (Giorgioni and Quitadamo, 2012)	AQ (Panicucci et al., 1998) CS (Tiwary et al., 2016); Pnators (Nebot and Mateu, 1990)	Evergreen broadleaf species yet rel. tolerant of drought and cold/strong wind. This tolerance of drought means it retains some capacity to sequester carbon (Mori et al., 2016) and deal with aerial pollutants such as SO_2 (Panicucci et al., 1998) under stressful conditions. Flowers known to attract certain Pnators (Hymenoptera, Diptera, Coleoptera and Lepidoptera) and provide nectar / pollen at an unusual / useful time of year (late winter) (Nebot and Mateu, 1990).
Weigela florida		AQ (Liu et al., 2017)	Good at trapping PM and Zn – Weigela florida 'Red Prince' ranked 5th out of 30 taxa by Liu et al. (2017).

recreation and security were mentioned in generic terms within papers (e.g. Gosling et al., 2016), but again there were few direct references to plant species. Pollution and noise research were focused on urban areas while much of the work on biodiversity and rainfall mitigation was predominantly implemented in rural locations (Table 3). Overall the greatest documented ESs (and some DSs) were associated with forest tree species that are also used as hedging subjects, for example *Fagus sylvatica* and *Carpinus betulus* or the common rural hedgerow species *Crataegus monogyna* (Table 3). This demonstrates the extent to which knowledge is still largely dependent on information from environmental/ecological studies in forestry or agriculture, rather than specifically in the urban context.

Only two studies to date have attempted to simultaneously rank the extent of provision of multiple services by urban vegetation (namely, Tiwary et al., 2016 and O'Sullivan et al., 2017). Tiwary et al. (2016) provide a particularly detailed guide on 15 tree/hedge species. In that study, *Fagus sylvatica* scores lowest overall despite having a positive impact on a number of ecosystem services; these authors take the view that this species' relatively narrow tree canopy decreases its service provision; a point that is irrelevant when grown as a hedge. Its positive attributes are backed up by other studies suggesting a good level of biodiversity support (Askew, 1980; Horák, 2011) and particulate pollution trapping (Sæbø et al., 2012). Van Renterghem et al. (2014) suggest *Fagus* has limited noise buffering capacity due to its open canopy, again a point that may be irrelevant in a hedge where regular pruning encourages a network of dense branches. When these nuances are taken into account, *Fagus* overall, would seem to merit its relatively high standing in this review.

Other species offering a larger range of ES include *Ilex aquifolium* and *Rosa rugosa* (although the latter is well-documented as being invasive on sandy soils). For other species, including *Ligustrum* spp., *Cotoneaster* spp. *Forsythia* x *intermedia* and *Laurus nobilis* there is only partial information available, for individual services. These species, however, may have the potential to deliver more ES, due to traits such as high evapotranspiration rates (cooling/rainfall management), dense canopy when grown as a hedge (PM accumulation / rainfall management) or waxy/hairy leaves (absorbance of PM / heavy metals) and these points should be practically tested. Some species provide outstanding contribution to certain services, but very low to others (e.g. *Berberis* good for noise mitigation, but low on particulate pollution trapping, Table 3). Research is required for a spectrum of short stature (often non-native) hedging species (e.g. *Hebe, Escallonia* and *Chaenomeles)*, as in some cases there is a complete paucity of information on their ESs/DSs, yet such species are common in urban conurbations.

Few species had net negative traits, and most provide at least intermediate level of several services with no negative impacts for example *Viburnum tinus, Laurus nobilis* (Table 3). Care should be taken however, in recommending species that are excessively vigorous and require high levels of maintenance (e.g. ×*Cuprocyparis leylandii*), especially where labour, resources or space may be limited, or that may become invasive in a particular locale. The selection of species with allergenic pollen is more problematic, for example *Carpinus betulus* with highly allergenic pollen (Frank and Ernst, 2016) and to a lesser extent *Thuja* and *Chamaecyparis* (Table 3). This is due to the fact, at least in some cases, that regular pruning of the hedges, may in itself remove the problem; plants being retained in a (non-flowering) juvenile state or any floral tissues being removed in the annual prune.

A number of the key ESs/DSs associated with hedges are summarised in the sections below, with particularly useful species for each being discussed.

3.3.1. Air quality and pollutant capture

The ability of hedge species to mitigate these environmental problems has received the most research attention in recent years. This has been driven by the negative effects of poor air quality on human health (respiratory and cardiovascular) (Pope and Dockery, 2006). The capacity of GI to remove both gaseous and particulate pollution is well documented, but figures about the extent of removal are dependent on the scale of measurements, meteorological conditions, plant characteristics and the compounds in question (Blanusa et al., 2015). In recent years, air purification systems using living plants have been introduced to roadside locations e.g. (Kao, 2015), and it is thought hedges or similar structured vegetation interventions may have a positive effect, at least in improving air quality at a local level (Abhijith et al., 2017; Abhijith and Kumar, 2019).

With particulate matter (PM) accumulation, certain plant traits are important, notably lanceolate-shaped and hairy leaves attracting most particulates (Leonard et al., 2016). Leaf hairs act by increasing the surface area onto which PM is deposited, but may also make it harder for PM to dislodge when leaves are moving (Neinhuis and Barthlott, 1998), a factor that leaf waxiness may also affect. Variation in the traits plants possess can mean a 10–20 fold difference in their capacity to trap PM (Sæbø et al., 2012). These authors also make a case for long term studies as performance between different species can vary between years, due to weather and physiological changes. *Fagus sylvatica* proved useful over both years of a 2-year study, whereas the evergreen, *Taxus baccata* demonstrate better performance only in the latter year; its data being consistent with the phenomena that chemical and morphological changes associated with leaf ageing increase deposition rates (Neinhuis and Barthlott, 1998).

Several studies investigated the use of hedge species as biomonitors of urban pollution, focusing on heavy metals (Rucandio et al., 2011; Mansour, 2014; Mori et al., 2015; Hu et al., 2014). There are significant differences between and within species in the affinity for particular metals (Rucandio et al., 2011). *Ligustrum ovalifolium* has affinity for scandium and vanadium (Rucandio et al., 2011), whereas *Elaeagnus* × *ebbingei* was better at trapping lead, chromium and copper (Mori et al., 2015). Care is required though, to select species that can tolerate such heavy metals as well as accumulate them (Sæbø et al., 2012). Other harmful compounds such as polycyclic aromatic compounds (PAHs) can also be sequestered by hedges, with *Laurus nobilis* showing the highest removal potential, *Photinia* × *fraseri* having the greatest tolerance to high concentrations (Fellet et al., 2016), but *Buxus sempervirens* accumulating the least (Librando et al., 2002).

Despite the perceived value of plants in improving air quality, it should be noted that some species may actually contribute to poor air quality through the release of biogenic volatile organic compounds (BVOCs), O_3 synthesis and the production of allergenic pollen, thus highlighting the requirement for appropriate species/cultivar selection. Urban plantings of *Laurus nobilis*, and particularly *Taxus baccata*, were found to emit only relatively low concentrations of monoterpenes (Noe et al., 2008a). *Taxus* was also an intermediate emitter of VOCs, but a good remover of O_3 (Paoletti, 2009). Pollen release and corresponding allergenic reactions in humans is one of the most significant DSs associated with GI. As mentioned, hedges may produce overall less pollen than equivalent trees as the regular pruning associated with them, tends to remove the more mature wood that normally forms floral tissues, as well as encourage more juvenile (non-flowering) growth. Nevertheless, hedge species that continue to form flowers may remain problematic. Members of the *Betulacea*, *Corylacea* and *Fagacea* are particularly associated with allergenic pollen, for example *Corylus avellana* (Lorenzoni-Chiesura et al., 2000), *Carpinus betulus* (Frank and Ernst, 2016) and *Fagus sylvatica* (D'Amato et al., 2007). There is also evidence that exposure to atmospheric pollutants (such as CO, O_3, SO_2) increases the allergenicity of pollen in some species (Cuinica et al., 2015).

3.3.2. Biodiversity

Hedge species in urban environment provide a crucial resource supporting a wide diversity of animal species through the provision of shelter, nest sites, food resources and corridors for movement (Beninde et al., 2015; Gosling et al., 2016; O'Sullivan et al., 2017). Despite most hedge species providing at least one of these opportunities, only 18 of the 43 species listed (Table 3) have been formally reviewed with respect to their value to wildlife (and most studies focus on birds and pollinating insects). Despite recent reviews of urban plants (Alexander et al., 2006; O'Sullivan et al., 2017), more research is required on how the extent, design and management of urban hedges affects biodiversity and how such factors influence other ESs and DSs. Moreover, it is not enough to consider the value of each hedge species in isolation. Planting a mixture of species to extend the flower or fruit availability periods, or using a range of plant species to provide a more heterogeneous structure (and hence greater niche opportunities) may be of particular value to wildlife. How the hedge species interact with other components of the urban environment is important too and species could be selected which fill a resource gap by providing flowers at important times or act as corridors between other areas of green space (Hall et al., 2017).

3.3.3. Noise mitigation

Noise, defined as 'unwanted sound', is a well-documented environmental stressor in the urban realm (Stansfeld et al., 2000). The WHO guidelines recommend < 40 dB at night and consistent exposure > 65 dB during the day is a concern (Anon, 2010). Thus noise reduction due to vegetation (e.g. up to 6–9 dB, Fang and Ling, 2003) may help keep thresholds below critical levels. A systematic approach to noise amelioration is hampered by inconsistent methodology and even differences in the metrics being measured. Nevertheless, plant characteristics such as biomass density, leaf size, and leaf orientation are known to influence the extent of noise attenuation (Van Renterghem et al., 2014; Capotorti et al., 2016). Wide, tall and multi-stratified vegetation belts with large-leaved evergreen species of dense canopies have been shown to provide overall good noise attenuation, although others suggest that the principal value of urban vegetation is the capacity to filter out high frequency noise from traffic (Tiwary et al., 2016).

Somewhat surprisingly, the number of studies on noise mitigation from hedges is limited, and some have researched mixed hedges, where the impact of individual species is hard to distinguish (Erdogan and Yazgan, 2009; Mutlu and Onder, 2012). Other studies focus on individual plants. Translating information, however, from these sources would suggest that *Berberis* spp. (Mutlu and Onder, 2012; Tiwary et al., 2016), *Ilex aquifolium* (Fang and Ling, 2003) and *Photinia x fraserii* (Fan et al., 2010) show promise as noise attenuators (reducing noise levels by 4–10 dB, depending on noise frequency). Only two studies compared genuine hedges composed of single species, with *Prunus laurocerasus* (Gratani and Varone, 2013; Van Renterghem et al., 2014) being cited as useful. Future research should focus specifically on hedges, not least because they have greater branch and leaf density than individual specimens, and so may have a greater impact on noise attenuation. Also, the shape and management of the hedge itself may be important: rather than having geometrically formal 'rectangular' and straight line linear hedges, would leaving shoots at the top and side of the hedge improve noise deflection? Future studies should address this and others factors associated with hedge design.

3.3.4. *Urban water management*

Managing rainfall is an increasing issue for urban areas due to the continuing reduction in the area of permeable surfaces (Perry and Nawaz, 2008; Warhurst et al., 2014). Approximately 25% of UK front gardens are paved over (impermeable) and 33% have no plants (Anon, 2016). Through carefully chosen and well-managed vegetation, however, gardens and green spaces could offer more protection against flooding (Cameron et al., 2012; Perry and Nawaz, 2008). The mode of action of vegetation is primarily two-fold: in intercepting and retaining the rainfall on the canopy (thus reducing and delaying rainfall runoff) and, more importantly, in water loss through evapo-transpiration which restores the soil's capacity to receive subsequent rainfall.

As with many other aspects of hedge research, focus on rainwater management has primarily been on the role of hedgerows in rural/agricultural landscapes (e.g. Ghazavi et al., 2008; Herbst et al., 2006). In an urban setting, GI installations such as rain gardens, bioswales, and green roofs have received much attention (Berretta et al., 2014; Cameron and Hitchmough, 2016), but the role of hedgerows in rainfall mitigation has largely been understudied. A study by Herbst et al. (2006) quantified the rainfall interception loss of agricultural hedgerows per unit ground area, and determined the horizontal extension of the zone which is being influenced by the presence of a hedgerow. Over a year these *Crataegus monogyna/Acer campestre* mixed hedgerows intercepted > 50% of the rainfall on the projected canopy area; and reduced the run-off from a cross-sectional area equivalent to twice the hedge height. Overall run-off was reduced by 24%, a value comparable to the most-effective broadleaf trees and only slightly lower than coniferous woods (Herbst et al., 2006). Generally, plants with fine needle-like leaves and larger total leaf surface areas (e.g. coniferous species) have been associated with greater rainfall retention/detention when studied as single trees or forest stands (Asadian and Weiler, 2009). However, hedge management (i.e. pruning) in urban and peri-urban context is anecdotally very intensive and is likely to radically alter total leaf area and the ratio of branches to leaves. Therefore, further research is urgently needed for this ES within an urban hedge context if hedges are to be used effectively as a tool in flood mitigation. Allied to this, some species such as *Forsythia* × *intermedia* with relatively high transpiration rates (even at low water availabilities, Cameron et al., 2006) may be useful for recharging soil moisture holding capacity; again this hypothesis needs confirming by further research.

3.3.5. *Health and well-being*

The value of urban green space on human health and well-being is currently the study of much investigation (van den Berg et al., 2010; Ward Thompson et al., 2012; van den Berg et al., 2015; Shanahan et al., 2015). There is still a paucity of information, however, on how green space *typology* affects psychological health. This includes any beneficial effects specifically associated with urban hedges. A point that needs addressing is how common these features are within the urban matrix, and how frequently they are 'within view' for people living within residential neighbourhoods. The review did not uncover any specific study associating hedges *per se* to human well-being, although some inferences could be made from the work of both Li et al. (2012) and Stigsdotter and Grahn (2003). *Lavandula* is often used as a short-stature hedge and has been linked with 'health restorative' properties, due to its blue and green hues (Li et al., 2012). Stigsdotter and Grahn (2003) suggest hedges are a key component of 'garden rooms' that provide 'refuge' for humans. Such 'rooms' have other features and so the precise contribution to hedges is difficult to determine, but hedges do seem to give a degree of seclusion as well as reduce/give the perception of less noise (Gidlöf-Gunnarsson and Öhrström, 2007). Nevertheless, a more precise role for hedges in this particularly important ecosystem service requires much greater substantiation.

4. Limitations of the review

The information in this review is collated from a range of different experiments, climates, planting contexts (e.g. hedgerows, but also hedge species planted as individual specimens), plant sizes and ages, metrics of measurement etc. We have been particularly surprised by the paucity of peer-reviewed papers which, when researching 'hedge' or a 'hedgerow', considered or provided the information about the species composition of the hedge. Species consideration was more often than not an afterthought, or an unintended consequence of studying urban or rural hedges, rather than a targeted study of species differences. Species choice does however influence the extent of services provision (Cameron and Blanuša, 2016), and we have therefore included the information on species when grown as individual trees, to increase our information base. As long as a species studied as an individual specimen can be also managed and grown as a hedge, we have chosen to extrapolate, with caution, potential services it might be able to provide in a hedge form. This could be seen as a weakness, as direct and neat comparisons are thus not always possible, but in our view this highlights the need for the development of standards for designing future research in this area. While inevitably incomplete, this review is a *starting point and an evolving document* collating in one place information on documented benefits, challenges and gaps in our knowledge about hedge plants.

Inclusion of health and well-being in the review, with few references returned for this topic may be seen as a limitation. It highlights though the mis-match between the limited details around composition of 'therapeutic' landscapes and the large numbers of papers now citing the importance of green space both in the formal literature for example (Douglas et al., 2017) but also increasingly translated into policy (e.g. GLA, 2017).

5. Conclusions and future work

Despite hedges being a common component of the urban matrix, this is the first aggregative systematic review of the benefits and drawbacks they provide based on their species composition. In a world that is rapidly urbanising and where there is pressure on land use through the increased densification of infrastructure (more houses per given space) the relatively compact nature of the urban hedge may have a pivotal role in ensuring our cities remain 'liveable', through effective ES delivery. Indeed, urban planning policies that fail to take proper account of urban hedges and their benefits, are likely to miss targets on urban pollution mitigation, functional biodiversity networks and human well-being. Already, hedges specifically located between roads and schools, or along trunk roads are being promoted to protect citizens from air pollution, but wider acknowledgment of their benefits is required to ensure a full and holistic approach to urban GI is adopted. Moreover, we desperately need information on *what species* to plant to optimise ES delivery. This review goes some way to addressing these deficiencies, and to identify new areas for research. We believe it will provide a platform to build information on, and become a key resource for landscape practitioners.

The review revealed that many hedge species provide a positive overall service. Indeed, no species was found to have a net negative association with ESs. Strong evidence on ES delivery exists for *Fagus sylvatica, Crataegus monogyna, Ilex aquifolium* and *Rosa rugosa* for which a number of individual services have been assessed. *Carpinus betulus* also proves promising, albeit a question remains as to whether this species flowers profusely when grown as a hedge and hence poses a problem *via* allergenic pollen. For other species, including *Ligustrum* sp., *Cotoneaster* sp. and *Laurus nobilis* there is only partial information available, for individual services. These species, however, should have the potential – due to their known structural or functional properties (e.g. hairy leaves, large and dense canopies, high transpiration rates) to provide extended benefits including cooling capacity and rainfall mitigation, which should now be practically tested. Some species provide outstanding contribution to certain services, but very low to others (e.g. *Berberis* good for noise mitigation, but low on particulate pollution trapping). In contrast to direct environmental parameters, our understanding of the health and well-being benefits and wider social implications around hedges is in its infancy. Secluded places and a feeling of closeness to nature are important factors in restoration from certain mental illnesses and hedges have a role to play in promoting these factors. They can provide a natural living barrier and a secure place for children to play within. Conversely, they can physically isolate individuals from their neighbours or even be a source of tension, but such factors are under-researched. The fact that the section on health evidence for individual species is sizeably smaller/less scientifically documented, highlights the importance of further species-specific research, which moves away from simple the notion that plants, in principle, support human health and well-being. The new layers of detail on the importance (or not) of plant form, colour, presence of certain sensory features, extent of planting, could form the basis of future work.

Information should also be sought on hedges' contribution to urban hydrological flows and ecological connectivity, and the extent to which they interlink with other forms of urban GI to ensure viable urban ecosystems and provide resilience against environmental extremes. Species and cultivar choice may be paramount in many of these incidences.

Finally, in our mind, one of the key practical limitations of information published thus far is that it overlooks more practical aspects of choosing and using hedges. The reality is that most garden / urban hedges are planted for protection, border definition, security (keeping strangers out and pets / children in) and seclusion, aesthetics and climate modification. We argue there is a practical need to define and quantify some of these aspects more systematically in the future.

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