Forestry Commission

Research Report

Delivery of ecosystem services by urban forests

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Introduction

The term 'urban forestry' was coined in the USA in 1894, though even there it did not come into broad use until the 1960s as the profession developed and the role and benefits of trees in urban areas became more widely understood. The first formal definition came in 1970: 'management of trees for their present and potential contributions to the physiological, sociological and economic well-being of urban society, which include the overall ameliorating effects of trees on their environment, as well as their recreational and general amenity value' (Jorgensen, 1970). The urban forest itself is defined as 'all the trees in the urban realm – in public and private spaces, along linear routes and waterways and in amenity areas. It contributes to green infrastructure and the wider urban ecosystem' (UFWACN, 2016), while 'urban areas' are classified as contiguous areas with a population of at least 10 000 people in England and Wales (ONS, 2005) or 3 000 people in Scotland (Scottish Government, 2014a). This report considers only the tree[1] component of the urban forest and focuses on four scale-based elements: 'isolated tree', 'line of trees', 'cluster of trees' (<0.5 ha) and 'woodland' (>0.5 ha).

Ecosystem services can be defined as the benefits that people derive from nature. The Millennium Ecosystem Assessment (MEA, 2005) and the UK National Ecosystem Assessment (UK NEA, 2011) categorised these as:

- provisioning services (providing benefits such as food and timber);
- regulating services (providing benefits such as carbon sequestration and flood protection);
- cultural services (providing benefits such as public amenity and opportunities for recreation),
- supporting services (providing benefits such as soil formation and biodiversity/habitats for wildlife).

Urbanisation and a changing climate are linked to more frequent and severe floods and heatwaves in Britain (Eigenbrod *et al*., 2011; Lemonsu *et al*., 2015; Met Office, 2016), while urban areas are also experiencing issues such as air pollution and poor physical and mental health of citizens (Sustrans, 2013; Cuff, 2016). Urban areas are growing and the percentage of people living in cities is also increasing (Champion, 2014) – currently approximately 73% of the population in Europe lives in cities (UN, 2014). Depending on how they are planned and managed, urban forests can pose an effective and nature-based solution to the negative impacts of urbanisation through the ecosystem services that they provide.

This Research Report sets out a typology of urban forest-based ecosystem services to link the provision of ecosystem services and disservices (those perceived as negative for human well-being) with the four scale-based urban forest elements. Conclusions are drawn from academic and other published literature from temperate climates on the key urban forest parameters (e.g. tree species, proximity to urban structures and land use) that influence the provision of ecosystem services, and under what circumstances disservices and trade-offs/synergies between different ecosystems services occur. This information can be used to inform urban forest planning and management in Britain to optimise ecosystem service provision for those who live and work in Britain's towns and cities.

[1] Tree is defined as a woody perennial plant typically having a single stem or trunk growing to a considerable height and bearing lateral branches at some distance from the ground (Oxford English Dictionary, 2016). The emphasis 'bearing lateral branches at some distance from the ground' distinguishes a tree from a shrub, which has multiple woody stems which arise at ground level forming a crown at a lower level (WSBRC, 2016). This definition of a tree can be developed through the distinction of 'stature', where small stature trees grow up to 6 m in height, medium stature trees grow to 6 to 12 m in height and large stature trees grow to over 12 m in height at maturity (Stokes *et al*., 2005).

Classifying the urban forest

To identify, quantify or value the ecosystem services provided by an urban forest it is necessary to define the specific aspects of the urban forest being considered and the factors which influence the ecosystem service provision. There is also a broader socio-economic context that provides important background to the way urban forests are valued; for example, how they can contribute to city and town identity, their role in attracting tourism and their contribution to the local economy. It is useful to bear in mind this broader context; however, this Research Report specifically focuses on the following key aspects:

- Physical – the scale, management and structure of the four urban forest elements considered.
- Context – location, land use and land ownership (including proximity to urban structures and people).

Physical – scale and management of urban forest elements

The 'isolated tree' is the smallest scale-based element of an urban forest; it is managed on an individual basis (Konijnendijk *et al*, 2006). The largest element is 'urban woodland' (measuring at least 0.5 ha in area and with a minimum width of 20 m; Forestry Commission, 2011), where trees are managed en masse using techniques more closely related to silviculture (Kenney *et al*., 2011). In between are a 'line of amenity trees', and a 'cluster of amenity trees', in which trees are typically managed on an individual basis under arboricultural techniques (Kenney *et al*., 2011), but are likely to be considered and valued together as a whole. Woodland tends to be able to provide provisioning and regulating services to a greater degree than sparsely planted areas due to the higher canopy cover (McPherson, 1994; Nowak and Crane, 2002), though an isolated tree can provide welcome shade and a sense of place within an urban environment.

Physical – structure of urban forest elements

The urban forest structure refers to both physical and biological attributes, such as tree density or spacing, size class distribution, age class distribution, tree health or condition, species composition, leaf surface area, canopy cover and biomass. Structural attributes can have a significant effect on the provision of ecosystem services, with larger and more mature trees typically providing a greater quantity and variety of ecosystem services than small and immature trees due to their larger canopies and stem diameter (Gill *et al*., 2007; McPherson *et al*., 2007).

Context – location and proximity to people

The locations on the continuum urban, suburban, peri-urban and rural are key in considering the benefits provided to society (Konijnendijk *et al*., 2006). Trees located in urban areas are likely to be visible to a large number of citizens, while peri-urban woodlands may be very important providers of recreational opportunities for some people. Similarly, the proximity of trees and woodlands to the built environment, hazards, places where people congregate and vulnerable people will determine to what extent they can provide certain ecosystem services such as shading, air purification or acting as a noise buffer.

Context – land use and ownership

The proportion of land covered by trees is significantly affected by land use and ownership status. Furthermore, land use and land ownership are important determinants of whether people can actually benefit from the services provided, as these will affect the accessibility and visibility of the trees. For example, trees located in public parks and along streets are likely to benefit a greater number of people (in terms of cultural services and shade provision) than those concealed in private residential gardens. Urban morphology types categorise land based on characteristic physical features and the human activities that they accommodate (Gill *et al*., 2008), and provide a useful way of identifying land use, ownership and ecosystem service provision.

Green infrastructure and the urban forest

Much of the literature on urban ecosystem service benefits refers to 'green infrastructure' rather than the urban forest, with the former defined as 'an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions' (Benedict and McMahon, 2006). In order to use this literature, it is necessary to consider how the urban forest contributes to green infrastructure. Table 1 shows the extent to which a green infrastructure typology (as set out in the *Handbook on green infrastructure*; Burgess, 2015) relates to the scale-based urban forest components discussed above, based on the views of the authors. Figure 1 presents the urban forest and its relationship to green infrastructure. Shrubs, grass and water are important components of green infrastructure and, following Dobbs *et al*. (2014) also contribute to the urban forest; these overlaps are presented in Figure 1.

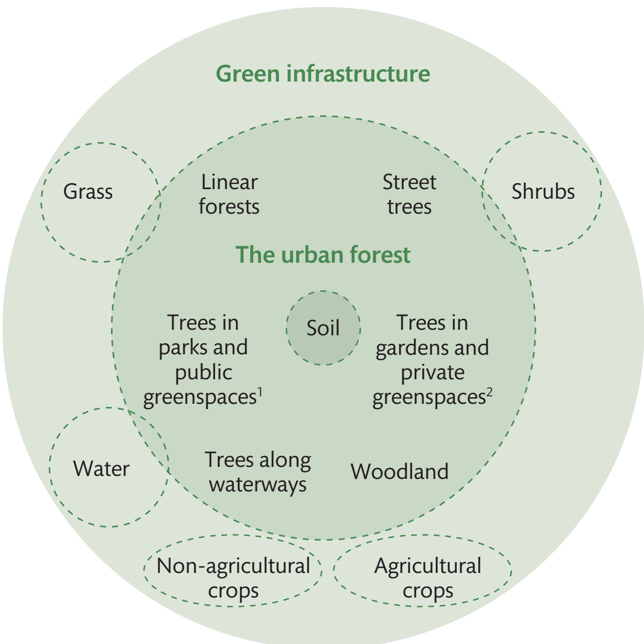
Table 1 Matrix of the relationship between urban forest components and green infrastructure types.

Green infrastructure typology*	Urban forest components			
	Single tree	Line of trees	Tree cluster	Woodland
Street trees and verges	Commonly related	Commonly related	Rarely related	Rarely related
Green roofs and walls	Sometimes related	Rarely related	Rarely related	Rarely related
Amenity spaces	Commonly related	Sometimes related	Sometimes related	Sometimes related
Derelict lands	Commonly related	Rarely related	Sometimes related	Sometimes related
Water management spaces	Sometimes related	Sometimes related	Sometimes related	Rarely related
Parks and gardens	Commonly related	Commonly related	Commonly related	Sometimes related
Land used for urban agriculture	Commonly related	Sometimes related	Commonly related	Rarely related
Civic spaces	Commonly related	Sometimes related	Sometimes related	Rarely related
Institutional grounds	Commonly related	Sometimes related	Sometimes related	Rarely related
Outdoor sports facilities	Sometimes related	Commonly related	Sometimes related	Rarely related
Green corridors	Sometimes related	Commonly related	Rarely related	Rarely related
Natural and semi-natural spaces	Sometimes related	Rarely related	Sometimes related	Sometimes related
Agricultural land	Sometimes related	Sometimes related	Sometimes related	Sometimes related

Commonly related   Sometimes related   Rarely related

* Source: Burgess (2015)

Figure 1 The urban forest and its relationship to green infrastructure (UFWACN, 2016).



[1] Examples of public greenspaces: civic and amenity spaces, green corridors, outdoor sports facilities, parks and gardens, urban orchards.
[2] Examples of private greenspaces: agricultural land, derelict lands, green roofs, institutional grounds, residential gardens, water management spaces.

Quantifying the ecosystem services provided by urban forests

Few studies have comprehensively analysed the full suite of services provided by the urban forest (Dobbs *et al*., 2011). Indeed, most studies that try to quantify urban ecosystem services focus on just one service (Gómez-Baggethun and Barton, 2013). This means that trade-offs and synergies between ecosystem services – when increasing provision of one service may increase or decrease the provision of another – are often ignored (Grêt-Regamey *et al*., 2013), as are the disservices – adverse ecosystem services – provided by trees. However, to optimise the benefits that the urban forest provides to people it is important also to assess and minimise the potential disservices and trade-offs (Dobbs *et al*., 2014).

Supporting services are often excluded from ecosystem service assessments to avoid double-counting and because their value is most easily defined via their contributions to provisioning, regulating and cultural services (Haines-Young and Potschin, 2013). This report therefore focuses on the latter categories only, and thus biodiversity, as a supporting service, is not explicitly covered. Some ecosystem services have been excluded from further consideration as they are thought to be less relevant to urban ecosystems (defined by Gómez-Baggethun and Barton (2013) as areas where the built infrastructure covers a large proportion of the land surface or where people live at high densities) or to urban forests in particular.

Table 2 sets out the relationship between urban forest components and the services and disservices they deliver. Provisioning and regulating are grouped according to the MEA categories. Cultural services, however, have been defined subsequently in the UK NEA follow-on work as encompassing the environmental spaces and cultural practices that give rise to a range of material and non-material benefits to human well-being (Church *et al*., 2014). Therefore, for the purposes of this report, the six well-being categories of benefit identified by O'Brien and Morris (2013) specifically focused on trees and woodlands are used to represent cultural services. These six categories of benefit have also been used by Sing *et al*. (2015) in a Forestry Commission Research Note on ecosystem services and forest management. Table 2 is based upon the literature reviewed for this Research Report (see later sections) as well as the views of the authors. In the absence of a published typology of ecosystem disservices, the disservices included in the table are those considered by the authors to be the most relevant to Britain's urban forests, based on the available literature.

Table 2 Matrix of the relationship between ecosystem services and urban forest components.

Ecosystem service		Urban forest components			
		Single tree	Line of trees	Tree cluster	Woodland
Provisioning	Food provision	Sometimes	Rarely	Rarely	Sometimes
	Fuel provision (woodfuel)	Sometimes	Sometimes	Sometimes	Rarely
	Wood provision	Sometimes	Rarely	Sometimes	Sometimes
Regulating	Carbon sequestration	Sometimes	Sometimes	Sometimes	Commonly
	Temperature regulation	Sometimes	Sometimes	Sometimes	Commonly
	Stormwater regulation	Sometimes	Sometimes	Sometimes	Commonly
	Air purification	Rarely	Commonly	Sometimes	Commonly
	Noise mitigation	Rarely	Commonly	Sometimes	Commonly
Cultural	Health	Rarely	Commonly	Commonly	Commonly
	Nature and landscape connections	Sometimes	Commonly	Commonly	Commonly
	Social development and connections	Sometimes	Sometimes	Commonly	Commonly
	Education and learning	Sometimes	Sometimes	Sometimes	Commonly
	Economy	Sometimes	Sometimes	Sometimes	Sometimes
	Cultural significance	Commonly	Sometimes	Sometimes	Commonly
Disservice	Fruit and leaf fall	Sometimes	Sometimes	Rarely	Rarely
	Animal excrement	Sometimes	Sometimes	Rarely	Rarely
	Blocking of light, heat or views	Sometimes	Sometimes	Sometimes	Sometimes
	Decrease in air quality	Sometimes	Sometimes	Sometimes	Sometimes
	Allergenicity	Sometimes	Sometimes	Sometimes	Sometimes
	Spread of pests and diseases	Sometimes	Sometimes	Sometimes	Sometimes
	Spread of invasive species	Sometimes	Rarely	Rarely	Rarely
	Damage to infrastructure	Sometimes	Sometimes	Rarely	Rarely
	Creation of fear	Rarely	Rarely	Rarely	Sometimes
	Tree and branch fall (especially during storms)	Sometimes	Sometimes	Sometimes	Sometimes

Commonly delivered   Sometimes delivered   Rarely delivered

Minimum requirements for ecosystem service provision

It is assumed herein that the ecosystem service (or disservice) is provided in sufficient volume for it to be of measurable benefit (or nuisance) to society; benefits that are delivered in such low quantities that quantification is problematic are not covered. Furthermore, where references to green infrastructure or greenspaces are used, it is assumed that trees are the primary factor in ecosystem service delivery. The case for trees as the key ecosystem service delivery component of green infrastructure is made throughout the UK NEA (2011), the Natural Environment White Paper (HM Government, 2011), the National Planning Policy Framework (DCLG, 2012), and by the many references quoted throughout this report.

Provisioning services

Food provision

Urban forests are regarded primarily as service providers rather than as sources of goods[2]; however, trees and woodlands have the potential to provide humans with food resources both directly (e.g. fruits, berries and nuts that are produced by the trees themselves) and indirectly (e.g. mushrooms and deer that reside in woodland habitats). This service is species specific, with only a few species able to produce edible food. Trees' provision of food is achieved through the conversion and storage of energy via photosynthesis into edible biological matter. Therefore, food resources may only be available at the end of a growth cycle. The key urban forest parameters that are reported to improve food provision from those species able to produce edible fruits, berries and nuts are summarised in Table 3.

The ecosystem service of food provision is primarily delivered by the 'single tree' or 'woodland' components of the urban forest. Fruit productivity is highest in medium

[2] Ecosystem 'goods' are typically tangible, traded products that result from ecosystem processes, and include food, fuel and wood.These are basic natural resources that we consume on a regular basis, and, as such, most ecosystem goods do not go unnoticed. By contrast, ecosystem 'services' tend to be thought of as intangible, not traded but increasingly valued, 'improvements in the condition or location of things of value', such as air purification or stormwater regulation (Brown *et al*., 2007). However, this distinction has generally been ignored since Costanza *et al*. (1997) merged goods and services into the broad class of 'ecosystem services'.

Table 3 Urban forest parameters that are reported to improve the ecosystem service of food provision.

Scale and management	Pest and disease control will ensure that trees stay healthy and thus produce higher quality fruit (Goldschmidt, 1999). Tree pruning and feathering techniques can result in greater yields of fruit (Robinson *et al*., 2007).
Urban forest structure	Trees with pyramid-shaped crowns produce more and better quality food than those with globe-shaped crowns due to the greater exposure to light (Robinson *et al*., 2007). The harvesting of fruit, berries and nuts, as well as ongoing tree maintenance, is easier for smaller trees (Robinson *et al*., 2007). Larger trees tend to produce larger fruit (Clark and Nicholas, 2013). Urban orchards in Europe are typically planted at a density of 500–600 trees per hectare due to diminishing returns (Robinson *et al*., 2007). Some species produce greater yields in monocultures due to resource competition from other species, while some fare better in polycultures with complementary processes (Rivera *et al*., 2004).
Location and proximity to people	Trees located near transport routes may have trace metal content (e.g. cadmium and lead) in their fruits, nuts and berries; however, they are less susceptible to pollution than vegetables (von Hoffen and Säumel, 2014). The closer food producing trees are to urban populations, the more likely people are to benefit from the increasingly popular trend of eating locally grown food (Clark and Nicholas, 2013). The feasibility of harvesting food from local trees or woods may be reduced where accessibility is difficult or impractical (e.g. due to the height of the tree or an adjoining busy road).
Land use and ownership	Fruit trees can be used as incentives for city dwellers to plant trees in private gardens (McLain *et al*., 2012). Publicly owned and accessible open space is likely to be best suited to the provision of public food trees (McLain *et al*., 2012).

density orchards (around 500–600 trees per hectare) though these are uncommon in urban areas. More common are individual trees, with pear and apple trees found to be in the top 10 most common species in London (Rogers *et al*., 2015). As noted previously, this service is very much species specific with only a few species able to produce edible food, while accessibility and proximity to people are the key delivery indicators.

Fuel provision (woodfuel)

Woody biomass is the accumulated mass, above and below ground, of the roots, wood and bark of stems and branches, and leaves of living and dead trees and woody shrubs. Through the processes of harvesting and combustion, woody biomass can be used as a source of heat, electricity, biofuel and biochemicals. Biomass harvesting occurs, to at least some extent, in the rural forests of most industrialised countries and is increasingly being considered in urban areas as a source of woodfuel. Two types of harvest are worth differentiating. These are 'biomass fuel' grown for the specific purpose of providing fuel (such as short rotation forestry crops) and 'woodfuel' (in the urban context this is the woody material generated by arboricultural operations, including crown reduction work and 'whole' tree removal). The key urban forest parameters that are reported to improve fuel provision are summarised in Table 4.

The ecosystem service of fuel provision (as woodfuel) is primarily delivered by the single tree, line of trees and tree cluster components of the urban forest as arboricultural arisings. Biomass from SRC/SRF is currently rarely a component of the urban forest, though could become increasingly important. The most important urban forest parameters for the woodfuel element of this service are accessibility, for example for woodfuel foraging, and proximity of the market, as high transportation costs can make the use of woodfuel economically unviable where being run as a commercial enterprise.

Wood provision

Trees can provide timber for construction, veneers and flooring, as well as wood chip and pulp for boards and paper. Timber production was the main focus of (rural) forestry in Britain before a shift in focus, over the last century, towards the delivery of multiple ecosystem services (Sing *et al*., 2015). Some urban trees offer considerable potential for wood or fibre provision, for example as quality hardwoods. However, there is concern over the compatibility of wood production and recreation in an urban setting. For example, certain activities can cause damage to trees (e.g. nails hammered into trees or accidental forest fires). As a result, the wood is sold as firewood rather than high-quality timber. A study into

Table 4 Urban forest parameters that are reported to improve the ecosystem service of fuel provision.

Scale and management	Soil nutrient availability is important for fast-growing species (Kimaro *et al*., 2007). Thinning and pruning of urban trees and woods produces 'arboricultural arisings' that can be harvested; this is likely to be the greatest source of woodfuel in England (McKay, 2006).
Urban forest structure	Fast-growing species and those with fast recovery rates (after harvesting) have a greater capacity to provide fuel; these include, for example, short rotation coppice (SRC) and short rotation forestry (SRF) (Velázquez-Martí *et al*., 2013). Larger trees (those with a large stem diameter and larger canopies) yield a greater quantity of woodfuel biomass (Velázquez-Martí *et al*., 2013). Large and poorly shaped branches/logs can cause processing problems (Bright *et al*., 2001). Some species have greater biomass in monocultures due to resource competition and/or overshadowing from other species (Cierjacks *et al*., 2013). Coppice species of limited height may be preferable in residential locations, and coppice can also occupy smaller sites (as small as 0.1 ha) than mixed woodland (Nielsen and Møller, 2008).
Location and proximity to people	The underlying terrain will need to be able to support the use of machinery, so soft uneven ground and steep slopes may not be appropriate (Hall, 2005). The proximity of the woodland to transport infrastructure and collection and processing facilities affects the feasibility of obtaining the resource (Hall, 2005). The proximity of the woodland to the market (point of use) determines the financial viability of the wood fuel due to transport costs (McKay, 2006).
Land use and ownership	There is potential to involve the public in obtaining biomass from short rotation coppice in public parks and woods, as part of a community renewable energy scheme (Nielsen and Møller, 2008). Accessibility (e.g. to private grounds) and exclusion on health and safety grounds will limit the ability of people to forage for arboricultural arisings, even though these may be plentiful (e.g. along transport corridors).

forests in the vicinity of Basel, Switzerland, found that reductions in timber value due to visitor-related damage to trees range from 19 to 53€ per hectare per year (Rusterholz *et al*., 2009).

There is a dearth of information on the size of the urban forest timber market and constraints to using the market. Information is also lacking on the appropriate scale, management, structure and location of potential wood-producing urban forests – therefore, no table is provided here.

Regulating services

Carbon sequestration and storage

Trees act as a sink for carbon dioxide (CO_2) by fixing carbon during photosynthesis and storing excess carbon as biomass. CO_2 sequestration refers to the annual rate of CO_2 storage in above- and below-ground biomass. Increasing the number of trees can therefore slow the accumulation of atmospheric carbon, a contributor to climate change. The ability of an urban forest to sequester carbon changes over time as trees grow, die and decay; a rotting tree will start to release its stored CO_2, becoming a CO_2 source. Human influences can affect CO_2 source/sink dynamics, with deforestation, the burning of wood and even management activities such as crown thinning resulting in a release of CO_2. The key urban forest parameters reported to improve carbon sequestration and storage are summarised in Table 5.

The ecosystem service of carbon sequestration and storage is delivered by all components of the urban forest, and the greater the proportion of land covered by trees the greater the sequestration and storage of CO_2. A good indicator of service provision is a high proportion of large diameter trees.

Temperature regulation

Low albedo materials (such as asphalt, tarmac and brick) absorb more short-wave radiation (sunlight) and store more heat than high albedo surfaces such as vegetation (which reflect more radiation), resulting in warmer air temperatures over urban areas compared to those over rural areas. This 'urban heat island' (UHI) effect is more pronounced during heatwaves – heat-related stress already accounts for around 1100 premature deaths per year in the

Table 5 Urban forest parameters that are reported to improve the ecosystem service of carbon sequestration and storage.

Scale and management	The total amount of CO_2 stored and sequestered is influenced by the area of existing tree canopy cover (McPherson, 1998). Carbon storage increases with tree density; hence woodlands are more effective than more sparsely planted urban land (Nowak and Crane, 2002). However, thinning can encourage growth. Patch size of deciduous woodlands in an urban environment is positively correlated with carbon density (Godwin *et al*., 2015).
Urban forest structure	On a per tree basis, carbon storage and sequestration is significantly greater in urban areas than in forests due to a larger proportion of large trees and faster growth rates resulting from the more open urban forest structure (Nowak and Crane, 2002). Ensuring diversity in species and canopy and understorey layers will increase carbon sequestration (Zhao *et al*., 2010). Larger trees tend to sequester and store more CO_2; indeed, CO_2 storage is proportional to the tree's biomass and diameter (McPherson, 1998). Carbon storage and sequestration depends also on a tree's growth rate and age class, with rates increasing to middle age and then diminishing towards post-maturity (Nowak and Crane, 2002). Trees with longer lifespans will have a greater positive effect on CO_2 uptake than short-lived trees as the frequency at which trees require planting, maintenance and removal (activities with associated fossil fuel carbon emissions) will be reduced (Nowak and Crane, 2002). Healthy trees will sequester and store more carbon (Nowak and Crane, 2002). Evergreen broadleaved forests have been found to sequester more CO_2 than coniferous forests due to their faster growth rates (Zhao *et al*., 2010).
Location and proximity to people	Trees that are subject to a greater level of anthropogenic disturbances (e.g. fragmented by roads) are found to store less carbon (Godwin *et al*., 2015). Poor rooting conditions, exposure to air pollution and heat, and severe pruning can lower biomass accumulation and carbon storage (Jo and McPherson, 1995).
Land use and ownership	CO_2 removal by the urban forest in residential areas has been shown to be greater than for other urban land-use types due to the higher density of trees (McPherson, 1998).

UK (Doick and Hutchings, 2013). Trees are not only good reflectors of short-wave radiation, but their canopies also shade low albedo surfaces that would otherwise absorb such radiation, reducing surface temperatures and convective heat. Trees also reduce warming of the local environment through the process of evapotranspiration where, by the evaporation of water from leaf surfaces, solar energy is converted into latent rather than sensible heat[3], thus 'cooling' the surrounding air and improving human thermal comfort. The key urban forest parameters that are reported to improve temperature regulation are summarised in Table 6.

The ecosystem service of temperature regulation is primarily delivered by the 'woodland' component of the urban forest; however, large isolated trees can be very effective in providing shading, as can clusters of trees in parks and lines of trees along streets. Delivery indicators include patch size of at least 3 ha, distances between (medium) greenspaces of 100–150 m, and trees that are tall, deciduous, with broad canopies and high LAI.

[3] Latent heat is associated with changes of state, for example from a liquid to a gas by evaporation, whereas sensible heat relates to a change in temperature of a gas and thus directly heats the atmosphere.

Stormwater regulation

Low albedo materials such as asphalt, tarmac and brick not only affect temperature, but these impervious surfaces also reduce the ability of rainfall to infiltrate into the soil and increase the speed at which it moves over the surface. This increases surface water runoff and peak discharge rates and raises the likelihood of flood events. Urban trees and woodlands regulate stormwater by intercepting and storing rainfall on their leaves, which either subsequently evaporates, or reaches the groundwater more slowly as a result of gradual release as throughfall. Trees also improve infiltration

Table 6 Urban forest parameters that are reported to improve the ecosystem service of temperature regulation.

Scale and management	Higher levels of tree cover provide greater solar obstruction and evaporation (Tyrväinen *et al.*, 2005). Larger greenspaces (>3 ha) have a greater cooling effect than smaller greenspaces (Vaz Monteiro *et al.*, 2016). Individual trees and clusters of trees have shown similar reductions in air temperatures (Bowler *et al.*, 2010a). Weed, pest and disease control will ensure that trees stay healthy, thus increasing the rate of evapotranspiration (McPherson *et al.*, 1999).
Urban forest structure	Broad tree canopies provide more shading than narrow ones (Armson *et al.*, 2013a). Tall trees provide more shading than short ones (Berry *et al.*, 2013). Trees with greater leaf area per unit of ground surface area, or 'leaf area index' (LAI, i.e. dense canopies), block a greater proportion of incoming solar radiation (Armson *et al.*, 2013a). Deciduous trees are particularly beneficial as they admit high levels of solar radiation in winter, while blocking it in summer (Akbari, 2002). Planting density should ensure canopy overlap to provide optimal shading (Berry *et al.*, 2013). Vegetation needs an adequate water supply to maintain cooling by evapotranspiration (Müller *et al.*, 2013).
Location and proximity to people	The demand for this service is largely dependent on where (vulnerable) people are. The use of greenspaces can alleviate people's perception of thermal discomfort during periods of heat stress (Lafortezza *et al.*, 2009). The cooling effect of greenspace decreases with distance from its boundary, up to a distance of around 300 m for large greenspaces (>10 ha) (Hamada and Ohta, 2010; Doick *et al.*, 2014a,b; Dugord *et al.*, 2014). The cooling effect of medium-sized greenspaces (3–5 ha) extends for approximately 70–120 m; thus placing greenspaces 100–150 m apart provides the best cooling (Vaz Monteiro *et al.*, 2016). Trees planted over grass (as opposed to asphalt or concrete) are the most effective cooling strategy (Armson *et al.*, 2012). To shade a building, a tree is best placed in close proximity (within 5 m) and to the west aspect of the building (Hwang *et al.*, 2015).
Land use and ownership	The warmest land uses are those where there is a prevalence of low albedo materials, with forested greenspaces being the coolest – though unforested greenspaces can also contribute to the daytime UHI effect (Gill *et al.*, 2008). Built-up areas with higher proportions and better composition of green structures (particularly trees) have significantly cooler surface temperatures than other built-up areas (Farrugia *et al.*, 2013).

into the soil by channelling water onto pervious surfaces around the stem, and through the soil along root channels. The key urban forest parameters that are reported to improve stormwater regulation are summarised in Table 7.

The ecosystem service of stormwater regulation is primarily delivered by the 'woodland' component of the urban forest in that tree cover will be higher in such areas. However, for a given height, isolated trees are more effective on a per tree basis due to their greater canopy size. Key delivery indicators for this service include overall canopy cover, trees with large stems, high LAI and multiple layers of branching, and a location adjacent to rivers or roads or upslope of urban areas (including upstream within peri-urban and rural areas).

Air purification

Trees remove air pollutants from the atmosphere mainly through dry deposition, a mechanism by which gaseous and particulate pollutants are captured by plants and absorbed through their leaves, branches and stems. Urban tree canopies are more effective in capturing particles than other vegetation types due to their greater surface roughness. Trees can also emit biogenic volatile organic compounds (BVOCs) that can contribute to ozone (O_3) and particulate matter (e.g. PM_{10} or $PM_{2.5}$) formation; this is discussed in a later section on ecosystem disservices. The key urban forest parameters that are reported to improve air purification are summarised in Table 8.

Table 7 Urban forest parameters that are reported to improve the ecosystem service of stormwater regulation.

Scale and management	Greater canopy cover increases rainfall interception (Inkiläinen *et al.*, 2013). Isolated, single trees use more water due to greater exposure and canopy size (Nisbet, 2005). Weed, pest and disease control will ensure that trees and canopies stay healthy, while arboricultural thinning affects structural density, thus reducing interception and increasing the speed with which rainfall reaches rivers (Xiao and McPherson, 2002).
Urban forest structure	Taller trees (~30 m) can reduce the amount of rainfall converted into throughfall more than smaller trees (~10 m), as aerodynamic turbulence and evaporation increase (Llorens and Domingo, 2007). Large-canopied trees play an important role in regulating stormwater through greater evapotranspiration (Gill *et al.*, 2007). Annual and peak event rainfall interception per tree increases with stem diameter, multiple layers of branching and rough bark surfaces (Xiao and McPherson, 2002). For small (canopied) trees, infiltration is more effective at reducing runoff than interception (Armson *et al.*, 2013b). Trees with greater LAI (denser canopies) can reduce the amount of throughfall through greater interception rates (Nisbet, 2005). Coniferous and evergreen broadleaved trees are more effective at intercepting rainfall than deciduous ones for which interception is significantly reduced during the leaf-off season (Xiao and McPherson, 2002). Fast-growing and deep-rooting trees transpire more water than slow-growing and shallow-rooting trees (Calder *et al.*, 2008). Structural diversity in (broadleaved) woodland increases its aerodynamic roughness and thus its evaporation rate (Calder *et al.*, 2008).
Location and proximity to people	Urban woodland is most effective at reducing flooding if located upslope of urban areas (Matteo *et al.*, 2006). Flooding is decreased and groundwater recharge increased when trees are located next to roads and rivers (Matteo *et al.*, 2006). Trees planted over pervious surfaces reduce surface runoff by more than those planted over impervious surfaces (Armson *et al.*, 2013b). Greening of sandy soils is more effective at reducing runoff than greening of clay soils (Gill *et al.*, 2007). In terms of the distribution of trees, studies typically focus on increasing tree cover in low tree cover areas across a city as a whole in order to have measurable reductions on runoff (Ellis, 2013; Sjöman and Gill, 2014). Peri-urban and even rural woodlands (in the riparian zone and floodplain) can contribute to flood alleviation in urban areas by delaying the downstream passage of flood flows (Forest Research, 2010).
Land use and ownership	Recategorising parkland to account for individual trees as distinct from amenity grassland results in more accurate scores for flood control (Farrugia *et al.*, 2013). The potential for maximising the possible contribution of green infrastructure to stormwater regulation is largely dependent on co-operative management of privately owned land (Ellis, 2013).

Table 8 Urban forest parameters that are reported to improve the ecosystem service of air purification.

Scale and management	The greater the (continuous) canopy cover and tree density, the greater the deposition of air pollutants (Alonso *et al.*, 2011). Unhealthy or stressed trees have reduced ability to remove air pollutants due to stomatal closure (Jim and Chen, 2008). Managing urban forests at intermediate scales (e.g. remnant patches around neighbourhoods) can reduce PM_{10} more effectively than landscape-scale tree cover (Escobedo *et al.*, 2011). Management of street trees and woodlands were found to be a cost-effective way of reducing PM_{10} compared to technological or policy measures such as the use of greener fuels (Escobedo *et al.*, 2008). The presence of street trees is associated with reduced prevalence of asthma (Lovasi *et al.*, 2008).
Urban forest structure	Conifers absorb the least O_3 and evergreen broadleaf species the most (Alonso *et al.*, 2011). Deciduous species assimilate more nitrogen oxides (NO_x) than evergreen species (Bowler *et al.*, 2010b). Coniferous trees are better at accumulating airborne $PM_{2.5}$ particles on their foliage than broadleaved species because of their thicker wax layer (Nguyen *et al.*, 2015). Trees with larger crown dimensions are more effective at air pollution removal (Alonso *et al.*, 2011). Air purification by trees is lowest in winter and highest in spring and summer due to leaf-on period (Baró *et al.*, 2014). The removal of air pollutants is related to total leaf area (Jim and Chen, 2008). Urban forests with diversified species and biomass structures are better for mitigating air pollution as overall canopy is increased (Jim and Chen, 2008).
Location and proximity to people	The availability of moisture in the soil will enhance a tree's ability to remove air pollutants (Baró *et al.*, 2014). Trees in closer proximity to a pollution source will be more effective at mitigating it, thus those between high pollution areas such as busy roads and vulnerable areas such as playgrounds, schools, hospitals and residential areas should be prioritised (Escobedo *et al.*, 2011). Conifers are generally less tolerant to high traffic-related pollution, so are less suitable for roadside plantings (Nguyen *et al.*, 2015). In narrow, busy streets tall and/or densely planted trees can reduce wind speed to the extent that pollutants may be trapped beneath the canopy, thus reducing air quality for pedestrians and cyclists – this is known as the street canyon effect (Vos *et al.*, 2013).
Land use and ownership	The greater the proportion of built area, the higher the level of PM_{10} exposure (Weber *et al.*, 2014).

The ecosystem service of air purification is primarily delivered by the 'line of trees' (specifically street trees – not so dense as to prevent air movement, due to their proximity to pollution sources) and 'woodland' components of the urban forest – the latter due to the higher tree cover. Key delivery indicators of this ecosystem service are total canopy cover, a high LAI, a high proportion of deciduous trees and the presence of trees near to pollution sources.

Noise mitigation

Urban areas can be a source of unwanted sound, for example road noise. Trees can mitigate urban noise through the scattering and absorption of (typically mid to high frequency) sound waves by the leaves, branches and stems, thus obstructing the pathway between the noise and the receiver. Woodland can additionally attenuate noise, particularly low frequency noise, through its generally soft and porous ground cover which can absorb sound waves. By providing an attractive visual barrier between the noise and the receiver, trees and woodland can also reduce the perceived volume and psychological impact of the noise – indeed perceived noise reduction can be more important than measured noise reduction – while birdsong and other sounds of the forest can also help to mask unwanted noise. The key urban forest parameters that are reported to improve noise mitigation are summarised in Table 9.

The ecosystem service of noise mitigation is primarily delivered by the 'woodland' component of the urban forest, though linear tree belts can also be effective if they are wide and densely planted. Other delivery indicators include trees with large stems, a high LAI and multiple low-level branches, and close proximity to the noise source.

Cultural services

Cultural services have been defined in the UK NEA follow-on work as encompassing the environmental spaces and cultural practices that give rise to a range of material and non-material benefits to human well-being (Church *et al.*, 2014). In an urban forest context, environmental spaces

Table 9 Urban forest parameters that are reported to improve the ecosystem service of noise mitigation.

Scale and management	The thinning of undergrowth and removal of scrub and deadwood within a woodland can have aesthetic benefits, thus improving people's noise tolerance (Tyrväinen *et al*., 2003).
Urban forest structure	Trees with broad leaves and/or a high leaf surface area can attenuate noise more effectively than narrow-leaved species (Heisler, 1977). Trees with multiple branches and forking at low levels provide more obstructions for the scattering of sound waves (Fang and Ling, 2003). Trees with dense crowns and foliage are most effective at reducing noise (Chen and Jim, 2008). Large trees attenuate more noise than small ones, with stem radius affecting the wavelength of the sound a tree scatters in a proportional manner (Huddart, 1990). Widely spaced trees along streets (>3 m) do not absorb noise, but may improve tolerance to noise (Heisler, 1977; van Renterghem *et al*., 2012). Visibility and width of a tree belt are more important for reducing noise than height and length (which become insignificant above 4 m and 50 m respectively) (Fang and Ling, 2003). Densely planted tree belts and deep woodlands have greater relative noise attenuation than sparsely planted trees or shallow woodlands (Huddart, 1990).
Location and proximity to people	Trees providing a partial visual barrier are more effective at improving noise tolerance than a full visual barrier. People expect the latter to fully block noise, so when it does not the sound can appear amplified; by contrast a partial barrier works most effectively in reducing the perception of sound (Heisler, 1977). Accessible green areas within and close to residential areas can moderate the adverse effects of traffic noise (including stress-related psychosocial symptoms) due to people's perception of them as positive sound environments and a place to go to escape noise-related stresses (Gidlöf-Gunnarsson and Öhrström, 2007; van Renterghem *et al*., 2012). Tree belts may be ineffective noise barriers for roads carrying fast-moving, heavy vehicles that pass close to residential areas (within 100 m); belts need to be dense, tall and wide (e.g. 30 m) to reduce sound to an acceptable level (Heisler, 1977). Noise barriers should be located close to the source rather than halfway between the source and the receiver (Heisler, 1977). At the macro-scale, scattered greenspaces can enhance noise attenuation more than clustered greenspace (Margaritis and Kang, 2016).
Land use and ownership	Areas with densely and heavily built urban structure types are associated with much higher noise levels than less dense, greener areas (Weber *et al*., 2014).

include parks and woodlands, as well as other geographical locations where people may interact with trees, such as along residential streets. Cultural practices are the activities that people undertake in such locations that link them to the natural world; these include (1) playing and exercising, (2) creating and expressing, (3) producing and caring and (4) gathering and consuming (Church *et al*., 2014). The authors define benefits as dimensions of well-being associated with these spaces and practices, including identities (such as sense of place), experiences (such as tranquillity) and capabilities (such as health) (Church *et al*., 2014).

For the purposes of this Research Report, the six well-being categories identified by O'Brien and Morris (2013) from 31 studies specifically focused on trees and woodlands are used to represent cultural services. These are health, nature and landscape connections, social development, education and learning, economy and cultural significance. People engage with trees in urban areas in a variety of ways (O'Brien and Morris, 2013). Direct use of a tree or woodland includes hands-on engagement such as gathering fruit, physically using the space for activities such as walking or picnicking, viewing trees through a window and active management or governance of a woodland or urban forest. People can also engage with trees in a non-use capacity. This includes existence value, that is just knowing that trees are part of the landscape, as well as virtual access via TV, computers or personal memory.

Health

This category considers physical well-being, mental restoration, escape and freedom, and enjoyment and fun. The benefit of health is strongly linked with recreation, which can be split into 'physical activities' such as walking, running and cycling, and 'relaxing activities' such as birdwatching, reading or having a picnic. The urban forest can support both forms of recreation, by providing a setting (an environmental space) where the activities can take place. Use of the urban forest is also associated with health benefits relating to being able to distance oneself from sources of anxiety or stresses associated with everyday life.

The key urban forest parameters that are reported to improve health are summarised in Table 10.

The well-being benefit of health is delivered by the 'woodland', 'tree cluster' (typically parkland settings) and 'line of trees' components of the urban forest – particularly contributing to mental well-being and enhancing quality of life. People report lower mental distress and higher well-being when living in urban areas with more greenspace in comparison to when they lived in areas with less greenspace (White *et al*., 2013). Delivery indicators for recreation provision are distance to (less than 500 m) and size of (at least 2 ha) a woodland or park (for which legal access must be provided), provision of facilities that improve accessibility and the range of activities that can be undertaken, large tree size and management to reduce understorey vegetation.

Nature and landscape connections

This category includes well-being types associated with sensory stimulation and feelings of connection to natural landscapes and wildlife. Benefits arise from visual aspects of an ecosystem (e.g. trees and woodland can obscure unsightly structures) as well as other senses such as the smell of honeysuckle or the sound of birdsong. These benefits can be obtained both by using the ecosystem directly (e.g. walking through a woodland), or, for visual aspects, from a distance (e.g. looking through a window of a building or vehicle). People can gain a sense of place from their local or favourite woodland, while physical interactions with trees, such as fruit picking or conservation volunteering, can add to feelings of connection with nature. The key urban forest parameters that are reported to improve nature and landscape connections are summarised in Table 11.

Table 10 Urban forest parameters that are reported to improve the well-being benefit of health.

Scale and management	People are more likely to walk or cycle to work if the streets are lined with trees (van den Berg *et al*., 2003; Nielsen and Hansen, 2007). Street trees have been found to decrease the risk of negative mental health outcomes such as depression (Taylor *et al*., 2015). Woodlands that are intensively managed or not managed at all have a lower recreation potential than those in between, while residue from thinning and harvesting are negatively associated with forest's recreational value (Edwards *et al*., 2012). Woodlands should be at least 2 ha in size to provide sufficient recreational opportunities (Coles and Bussey, 2000). Improvements to local woodlands (e.g. construction of footpaths, removal of litter and clearing of sightlines) can significantly improve local people's attitudes to woodlands as places for physical activity (Ward Thompson *et al*., 2013).
Urban forest structure	Broadleaved trees have greater recreational value than coniferous trees (Edwards *et al*., 2012). Large, tall, mature trees are most preferred as recreational features within European forests (Edwards *et al*., 2012). Light, open woods with widely spaced large trees provide better recreational opportunities than dense belts of small trees or woodlands with understorey (Nielsen and Jensen, 2007). Blocks of woodland with interweaving circuits offer more opportunity for exploration than narrow woodlands, particularly for those <5 ha (Coles and Bussey, 2000). Diversity in tree species, woodland structure and habitats offers more recreational opportunities (Ryan and Simson, 2002).
Location and proximity to people	People should have access to a woodland of at least 2 ha within walking distance (500 m) from their home, and a woodland of at least 20 ha within 4 km of their home (Woodland Trust, 2014). The urban deprived and Black, Asian and Minority Ethnic groups are more likely to access urban rather than rural nature compared to other population groups (Burt *et al*., 2013). Facilities such as paths, signs, benches, picnic areas, car parks and toilets will improve the usability of urban and peri-urban woodlands, though should be in keeping with the woodland scene (Doick *et al*., 2013). Accessibility of woodlands for recreation can be reduced by the need to cross busy roads (Coles and Bussey, 2000). Children in wealthier areas have greater access to (better) woodlands than children in more deprived areas (Seeland *et al*., 2009).
Land use and ownership	Time spent in privately owned greenspace has a greater impact on reducing stress than time spent in public greenspace (Grahn and Stigsdotter, 2003; CJC Consulting *et al*., 2005). There is often little awareness of woodland ownership, which can lead to lack of confidence to visit and confusion over what spaces people can access (Carter *et al*., 2009).

Table 11 Urban forest parameters that are reported to improve the well-being benefit of nature and landscape connections.

Scale and management	Individual trees, especially veteran ones, can provide great character and sense of history to a place (Scottish Government, 2014b). Individual trees have a positive effect on the perceived aesthetics of urban squares, enhancing city image, duration of visit and the willingness to revisit (Raškovič and Decker, 2015). Lines or clusters of trees can provide aesthetic enhancements to streets, civic spaces and parks (Coles *et al.*, 2013). Woodlands should be of a suitable size (minimum of 2 ha) to create a woodland environment (Coles and Bussey, 2000). The greater the number of greenspaces the greater the overall aesthetic value, though with diminishing returns (Mitchell and Popham, 2007). Management activities such as selective arboricultural thinning and undergrowth clearance (as well as removal of litter and graffiti) can improve visual perceptions (Tyrväinen *et al.*, 2003).
Urban forest structure	Large, mature trees are generally more aesthetically pleasing than small, immature ones (Tyrväinen *et al.*, 2005), though this is less important in residential environments (Coles *et al.*, 2013). Broadleaved or deciduous species are typically preferred to coniferous ones, though mixed woodlands are preferred overall (Coles and Bussey, 2000; Gerstenberg and Hofman, 2016). Crown size and density are both positively related to people's preferences, with globe-shaped crowns particularly preferred (Gerstenberg and Hofman, 2016). The smell of damp wood after rain and of pine trees, and the sounds of walking on crunchy leaves, bird song and the wind in trees, add to feelings of connection with nature (O'Brien *et al.*, 2014). Perceived naturalness can enhance the visual appeal of a woodland, and thus the use of native species may be beneficial (Ryan and Simson, 2002). Woodlands with greater structural complexity (more canopy layers and different species) are preferred (Coles and Bussey, 2000). Woodlands should be open with well-spaced trees in order to improve visibility and thus feelings of security (Nielsen and Jensen, 2007). Clear views with low-density understorey vegetation are associated with increased pleasure and are preferred by visitors (Tyrväinen *et al.*, 2003). Visual variation (i.e. combining mature stands with smaller trees, as well as the presence of other habitats such as water) is more aesthetically pleasing (Tyrväinen *et al.*, 2005). People prefer/self-report high benefits from greenspace that they perceive to have higher biodiversity (Dallimer *et al.*, 2012).
Location and proximity to people	Trees and woodlands must be visible and in fairly close proximity for the service of aesthetic enhancement to be provided, as evidenced by the effect of green views on property prices (Jim and Chen, 2006). Access to and views of greenspace within a workplace have significant benefits for well-being as well as increased productivity (Grahn and Stigsdotter, 2003). There is enhanced recovery from illness or surgery when patients have views of trees from hospital (Ulrich, 1984).
Land use and ownership	A view of a (publicly inaccessible) greenspace can be as effective for mental well-being as having access (Grahn and Stigsdotter, 2003).

The well-being benefit of nature and landscape connections is delivered by all four scale-based components of the urban forest, with maturity being particularly important for individual trees and a general preference towards broadleaf species. Key delivery indicators include the visibility of the trees or woodland, a diversity of species and habitats, large tree size and management to reduce understorey vegetation.

Social development and connections

Activities undertaken within woodlands and parks can strengthen existing social relationships, while organised activities within treed environments can create the opportunity for new relationships, including people's involvement with volunteer groups and community forests (known as social capital). As well as providing a setting and gathering place for people, the woodland itself can bring people together as a symbol of history, territoriality or mutual interest (e.g. birdwatching or mushroom picking). The key urban forest parameters that are reported to improve social development are summarised in Table 12.

The well-being benefit of social development is primarily delivered by the 'woodland' component of the urban forest, though parks and housing estates containing 'tree clusters' are also important. The delivery indicators for this service

Table 12 Urban forest parameters that are reported to improve the well-being benefit of social development.

Scale and management	The encouragement of community management of woodlands (e.g. tree planting schemes or volunteer conservation groups) can engage people in social activity and improve self-esteem (Elmendorf, 2008). Management activities that improve aesthetics will encourage community use (Tyrväinen *et al.*, 2003).
Urban forest structure	People are more likely to congregate in attractive woodland settings; thus tall, mature trees are preferred (Tyrväinen *et al.*, 2005). Native species may be considered more representative of an area and thus contribute to sense of place and community spirit (Ryan and Simson, 2002). Large and more densely planted woodlands, and those with homogeneous trails, can mask the number of users, easing perceptions of overcrowding which can reduce the quality of social encounters (Coley *et al.*, 1997). Social contact and community cohesion can be fostered by woodlands and small groups of trees near housing estates (Kuo, 2001).
Location and proximity to people	The use of outdoor spaces and the amount of social activity that takes place within them increases with the presence of trees and grass (Coley *et al.*, 1997). Woodlands and greenspaces in closest proximity to where people live are more likely to be used for social activities (O'Brien and Morris, 2013). The lower prevalence of higher quality woodlands in deprived areas excludes their use by those who may benefit most from social interaction (Seeland *et al.*, 2009). Urban parks serve as settings for interacting with families, helping immigrants (or other people new to an area) to develop memories and emotional connections to their environment, and to preserve their traditions and culture (Peters *et al.*, 2016).
Land use and ownership	Woodland must be publicly accessible for there to be social cohesion benefits (Seeland *et al.*, 2009). The encouragement of community management of woodlands (e.g. tree planting schemes or volunteer conservation groups) can engage people in social activity and improve self-esteem (Elmendorf, 2008).

are short distance to and public accessibility of the woodland or park, and management activities that improve aesthetics and encourage community use.

Education and learning

This category includes personal development for people of all ages, gained through informal learning, such as parents teaching their children tree names or where wood and paper comes from, and formal education via approaches such as Forest School (O'Brien, 2009). Learning can also take place through activities such as volunteering, apprenticeships and play for children. Gill (2011) argues that outdoor educational approaches are critical in connecting children and young people with nature, while Kuo (2001) found that street trees in deprived residential areas are associated with significant benefits for children's cognitive function; other benefits include physical, social and personal development and affective (emotional) benefits (Dillon and Dickie, 2010). The key urban forest parameters that are reported to improve the well-being benefit of education and learning are summarised in Table 13.

The well-being benefit of education and learning is primarily delivered by the 'woodland' component of the urban forest, though 'tree clusters' and 'single trees' can also be important. The delivery indicators for this service are short distance to and public accessibility of the woodland or park. Management activities should encourage learning opportunities through interpretation, organised activities and allowing school and specific interest groups to carry out education activities on site.

Economy and cultural significance

The urban forest can contribute to the economy by encouraging inward investment, boosting tourism, providing a setting for recreation industries such as climbing and paintballing, and by enabling environmental cost savings (Eftec, 2013). These are indirect 'place setting' benefits of the urban forest. However, the urban forest can also contribute directly to the economy through the generation of new employment, such as arboricultural consultants and tree surgeons and, to a lesser extent, through the provision of food, fuel or wood products. Wolf's (2004, 2005) studies focus on the perceptions of trees among consumers in business settings and how they rated and enjoyed retail areas and roadsides with tree cover. It is suggested that trees can be significant elements in place marketing – large trees and a full canopy were

Table 13 Urban forest parameters that are reported to improve the well-being benefit of education and learning.

Scale and management	Access to safe outdoor spaces is important for young people in deprived areas (Strife and Downey, 2009). Provision of play opportunities for children is important in enabling them to learn about risk (Gill, 2011).
Urban forest structure	Development of social interaction skills can be fostered by woodlands and small groups of trees near housing estates (O'Brien et al., 2010a). Martensson et al. (2009) found lower prevalence of attention deficit disorder symptoms among children whose pre-schools had more green characteristics such as trees. Those involved in recreation activities in woodlands can gain or improve skills associated with their activity (O'Brien and Morris, 2013). Involvement in urban tree conservation volunteering can provide a range of opportunities for all ages to learn and develop new skills (O'Brien et al., 2010b).
Location and proximity to people	Schools close to wooded areas potentially find it easier to access these spaces for outdoor learning opportunities (O'Brien and Murray, 2007).
Land use and ownership	Woodland must be publicly accessible or arrangements made with a private woodland owner in order to use them for learning (O'Brien and Murray, 2007).

enjoyed most. A number of studies have also looked at trees and woods and their influence on residential property prices in urban areas. All found that trees and woods increased property value (Tryvainen and Miettinen, 2000; Donovan and Butry, 2010).

The urban forest also contributes to experiences and interpretations of the symbolic, cultural and historical significance of woods and trees, for example through literature and art, associations with folk heroes (e.g. Robin Hood), associations with festivities (e.g. Christmas trees), and associations with British culture (e.g. the oak leaf is represented in the logos of a number of British organisations, such as the National Trust and the Woodland Trust) and through heritage trees. People's memories of tree or woodland-based childhood activities can add meaning and identity to the urban forest, while there are also spiritual and religious associations, such as the planting of a tree to mark the birth of a child or the death of a family member.

Tables are not provided for the well-being benefits of 'economy' and 'cultural significance' as there is less evidence for these categories related to the scale, structure and location based elements discussed in this Research Report.

Summary of minimum requirements for ecosystem service provision

This section brings together the key urban forest parameters for each of the provisioning, regulating and cultural services discussed above, based on the available evidence (Table 14). It is important to note that there are still evidence gaps and uncertainty relating to some services.

Table 14 Summary of delivery indicators for ecosystem service provision.

Ecosystem service	Scale and management	Urban forest structure	Location and proximity to people	Land use and ownership
Provisioning				
Food provision	Single tree Woodland	Species specific 500–600 trees per hectare	Close to people	Accessible land
Fuel provision	Woodland	Fast-growing species Large stems Large canopies	Close to market, infrastructure and processing facilities	Accessible land (for arboricultural arisings)
Regulating				
Carbon sequestration	Proportion of land cover by trees Large patch size	Large stems	(n/a)	(n/a)
Temperature regulation	Single tree through to woodland Large patch size (>3 ha)	Broad canopies Tall trees High LAI Deciduous species	Close to buildings Close to where people congregate Shading of sealed ground	Building density and sky view factor
Stormwater regulation	Woodland	Large stems Large canopies High LAI Multi-layer branching species	Upslope of areas vulnerable to flooding Adjacent to roads and rivers	Surface permeability
Air purification	Line of (street) trees Woodland	Large canopies High LAI Species specific	Close to pollution source	(n/a)
Noise mitigation	Line of trees Woodland	Large stems High LAI Low-level branching species	Close to noise source Visible and attractive	(n/a)
Cultural				
Health	Cluster of trees through to woodland Patch size >2 ha Facilities to improve accessibility Undergrowth clearance	Tall trees Large stems Widely spaced Light, open structure	Close to people (<10-minute walk)	Accessible land
Nature and landscape connections	Single tree through to woodland Undergrowth clearance	Mature trees Tall trees Large stems Other habitats	Visible and attractive	(n/a)
Social development and connections	Cluster of trees through to woodland Facilities to improve accessibility Undergrowth clearance Community (co-) management	Mature trees Tall trees Large stems	Close to people (<10-minute walk)	Accessible land
Education and learning	Woodland Provision of play opportunities Encouragement of learning activities	Variety of green characteristics	Close to people	Accessible land

(n/a) = not applicable

Ecosystem disservices

Disservices are defined as 'functions or properties of ecosystems that are perceived as negative for human well-being' (Lyytimäki and Sipilä, 2009). The most commonly reported disservice in the literature is the formation of ozone (O_3) and particulate matter (e.g. PM_{10} or $PM_{2.5}$), which contribute to respiratory illnesses, following the emission of biogenic volatile organic compounds (BVOCs) by certain trees. These reactions occur as the wind mixes and disperses the BVOCs, and therefore this disservice can affect a wide area. Other disservices with a diffuse impact include vehicle and machinery exhaust emissions during tree or woodland maintenance (carbon dioxide and particulates); allergenicity – the release of pollen by trees can affect human health, prompting an allergic response in around one-third of the world's population (Cariñanos *et al*., 2014); and the facilitated spread of pests and diseases through the provision of hospitable habitats from which they can become established and advance. For example, non-native pests and diseases of pine, oak, alder, horse chestnut, ash and larch are now prevalent in Europe, with urban trees and woodlands providing an entry point to unaffected UK locations and a place to become established before spreading across the country. Similarly, urban areas and ornamental gardens are often the entry point for new trees and shrubs to UK arboriculture and horticulture. Some are subsequently found to be invasive, including the foxglove tree (*Paulownia tomentosa*) and the tree of heaven (*Ailanthus altissima*), and become widespread beyond the managed area to which they were introduced.

Commonly reported location-specific ecosystem disservices include reduced solar access, whereby trees cast unwanted shade on buildings (as well as gardens) and an associated increase in heating costs during the winter, and tree root-induced damage to pavements, which can cause access problems and pose a trip hazard. There are also problems caused by dropped fruit, leaves, branches, flowers and seeds from the trees themselves, or from excretions from other species using the trees, such as bird droppings or honeydew (a sugary sap excreted by aphids). As well as being considered visually unattractive, fallen fruit can result in slippery pavements or a temptation for anti-social behaviour, fallen leaves and branches can pose additional hazards, while bird droppings and honeydew on parked cars are a particular nuisance. Other location-specific ecosystem disservices include building subsidence – though prevalence is low and only occurs in areas with shrinkable clay – and the creation of fear due to trees and woodlands causing dark shadows, particularly in areas where anti-social behaviour is prevalent. Table 15 highlights the factors that can cause urban forests to produce ecosystem disservices.

It is imprudent to enhance urban forest ecosystem service delivery without also considering how to minimise ecosystem disservices delivery. Just as ecosystem services can be enhanced through the planning, designing and management of the urban forest – including species selection, planting density and location – disservices can also be planned out. Many disservices are attributable to specific species, so either these species should be avoided or a greater variety of species planted so that adverse effects are diluted to an acceptable level. Particular locations can also be avoided; for instance, fruiting trees or those with shallow roots may be considered unsuited for roadside verges and pavements. In some cases, regular pruning and management can reduce the likelihood of various disservices occurring: tidier and more open woodlands are less likely to cause fear; trees that are prevented from growing too large are less likely to damage infrastructure; regular pruning of ornamental trees can lead to reduced flower production and thus the amount of pollen released; and trees that are monitored for ill-health can have affected limbs removed or crowns reduced to decrease the likelihood of branch loss or tree failure.

Table 15 Urban forest parameters that are thought to exacerbate the effect of ecosystem disservices.

Ecosystem disservice	Scale and management	Urban forest structure	Location and proximity to people	Land use and ownership
Fruit and leaf fall	Single tree through to line of trees	Female trees (fruit) Species specific (fruit) Lack of diversity in species to dilute the effect (fruit) Deciduous species (leaf)	Pavements Roads and railways Civic spaces Close to drains	Accessible land
Animal excrement	Single tree through to line of trees	Species specific (honeydew)	Pavements Car parking locations Civic spaces	Accessible land
Blocking of light, heat or views	Single tree through to woodland	Tall trees Large stems Large canopies Evergreen species	Close to buildings (west aspect, within 5 m)	Private or accessible land
Decrease in air quality	Single tree through to woodland	Species specific Lack of diversity in species to dilute the effect	Areas with existing NO_x problems Close to people	(n/a)
Allergenicity	Single tree through to woodland Lack of pruning and management	High tree density Large canopies Tall trees Multi-branching species Male trees Species specific Lack of diversity in species to dilute the effect Ornamental / exotic species	Close to people	(n/a)
Spread of disease and pests	Single tree through to woodland	Species specific Lack of diversity in species to dilute the effect Ornamental/exotic species	Warmer areas	Lack of biosecurity
Spread of invasive species	Single tree	Species specific Ornamental/exotic species	(n/a)	Private or accessible land
Damage to infrastructure	Single tree through to line of trees Lack of pruning and management	Tall trees Large stems Large canopies Shallow-rooting species	Pavements Areas with shrinkable clay Close to buildings and infrastructure	Private or accessible land
Creation of fear	Tree cluster through to woodland Lack of pruning and management	High tree density Low-level branching species Dense undergrowth Dark, closed structure	Infrequently used areas Run-down areas Unlit and poorly lit areas	Private or accessible land
Tree and branch fall (especially during storms)	Single tree through to woodland	Older trees Diseased trees	(Direct) risk to people under the tree Close to property – buildings and cars	Private or accessible land

(n/a) = not applicable

Associations between urban forest-based ecosystem services

This section discusses the main synergies and trade-offs between the different ecosystem services and disservices, based on the urban forest parameters discussed in the preceding sections.

Synergies

The urban forest parameters that are beneficial and common to all of the ecosystem services featured in this Research Report are the need for trees to be healthy and the use of species that are climate resilient and tolerant of extremes in temperature as well as drought and waterlogging. Extensive tree canopy cover across an urban area as a whole (and to a lesser extent within a woodland) is also beneficial for many of the ecosystem services discussed. The food and fuel provisioning ecosystem services further require that trees are regularly pruned, and that the land is publicly accessible (unless the food or fuel is for private consumption or sale). Like fuel provision, carbon sequestration is greatest for fast-growing species and those with large stems (i.e. a large biomass).

The regulatory ecosystem services of temperature and stormwater regulation, air purification and noise mitigation are all dependent on providing some sort of physical barrier: to solar rays, precipitation, pollutants or sound waves, respectively. These barriers are more effective with trees that are tall, with large stems, broad or large canopies, a high leaf area/density (LAI) and multiple layers of branching, and with woodlands that have high structural diversity (e.g. in terms of canopy layers and number of species). Air purification, noise mitigation and carbon sequestration also benefit from high tree density, though some degree of openness is also important.

The provision of many cultural services is enhanced with trees that are tall, with large stems and broad or large canopies, and with woodlands that have high structural diversity. In addition, people generally prefer native species, regular but not excessive pruning and other maintenance, while aesthetics and recreation potential are enhanced through the incorporation of other habitats such as water bodies and grassy areas. It is essential that the trees and woodlands are near to people, as well as publicly accessible, for the provision of cultural services.

Woodlands should be at least 2 ha for health and social development benefits to be maximised, while carbon sequestration and temperature regulation are also more effective with larger patch sizes. Due to the higher tree density, woodlands are also more effective for stormwater regulation, while a cluster or line of trees or a woodland is beneficial for air purification and noise mitigation. All scale-based urban forest elements – including single trees – can provide food and fuel, store carbon, regulate temperature and enhance aesthetics.

Overall, there are greatest synergies among the following delivery indicators for ecosystem service provision: trees which are tall with large stems and canopies and a high LAI; large patch sizes with good structural and species diversity; trees which are close to people and sources of environmental harm; and trees which are visible, attractive and accessible. Where land-use change is being planned, careful consideration to attain these synergies can lead to optimised delivery of a 'bundle' (Hansen and Pauleit, 2014) of ecosystem services.

Trade-offs

The urban forest parameters required for the provision of certain ecosystem services can be in conflict with each other. For example, the presence of multi-layer branching species and those with low branches, as well as understorey vegetation, can be beneficial for stormwater regulation, air purification and noise mitigation, yet are often incompatible with the cultural ecosystem services as they are considered to be less visually attractive. Similarly, dense woodlands reduce light and visibility; on the one hand this can potentially create fear, but on the other hand dense woodlands can mask the number of woodland users and thus ease perceptions of overcrowding.

There are numerous examples of differences in ecosystem service provision between broadleaf or coniferous, deciduous or evergreen species. For the purposes of aesthetic enhancement or recreation potential, people generally prefer broadleaf species, though there is also evidence to suggest that mixed woodlands are preferred to exclusively broadleaved ones. Broadleaf species also mitigate noise more effectively due to their broader leaves.

However, most broadleaf trees in Britain are deciduous, meaning that they drop their leaves in autumn and do not regain them until the following spring. Evergreen trees (which in Britain are mainly conifers) are therefore more effective at regulating stormwater given that most (heavy) rain occurs in the leaf-off period of late autumn, winter and early spring. In contrast, for temperature regulation, deciduous (broadleaf) trees are often preferable to evergreen ones (conifers), as they provide more shade in summer when it is most needed. In terms of air purification, deciduous species assimilate more nitrogen dioxide than evergreen ones; evergreen broadleaf species absorb more ozone than deciduous ones, which in turn absorb more than conifers; and coniferous trees capture the most particulate matter, though they are also less tolerant to traffic-related pollution, so may be unsuitable as street trees.

Certain species of tree emit high levels of BVOCs, while others are associated with pollen allergenicity. In these cases, the number of problematic trees can be reduced and the overall diversity of tree species present increased leading to both a reduction and a dilution of the disservices.

The tree's location can also pose a dilemma, with those in close proximity to buildings providing summer shade and reducing air conditioning costs, while leading to increased risk of causing infrastructural damage. Street trees are particularly beneficial for air purification (except where the canyon effect in narrow streets holds pollutants at street level), temperature regulation and aesthetic enhancement; however, tree roots can also cause the break-up of pavements, while fruit fall onto pavements can pose a slip hazard, as well as being unsightly.

The solution to most of these trade-offs, and to enhancing synergies, is ensuring that the right tree is planted in the right place – a situation that can be hard to achieve given the wide range of stakeholders who own, use and care for the trees that make up urban forests and given the mosaic of public and private land uses in which these trees are planted. A management plan, however, can provide an overarching strategy. The plan would need to include an objective to optimise ecosystem service delivery as part of a long-term vision, should include guidance on preferred species, planting locations and management, and should be written in a style and disseminated in ways that reflect the range of stakeholders concerned. It should also include a commitment to periodic – typically five yearly – revision of the plan and its delivery in response to changes in local and regional priorities.

Conclusion

As noted by Konijnendijk *et al*. (2000), woodlands, parks and streets are given almost equal attention in the urban forest literature, with papers focusing on the entire urban forest or green infrastructure also being common. However, there is very little reference in the literature to the scale-based elements of individual, lines and clusters of trees. The lack of reference to scale-based elements is particularly prevalent for studies on park trees, as it is rarely specified whether these trees are isolated, in lines or clusters, or within larger groups of more than 0.5 ha in area and 20 m in width (and thus a woodland). Therefore, while it is clear from the literature that it is the tree element of the natural environment that is providing greater ecosystem services to society, and by definition these are components of the urban forest, the literature is often less clear which component part(s) of the urban forest are primarily responsible for delivering specific ecosystem services. By gathering the available knowledge, this Research Report goes a long way to drawing these distinctions – distinctions that are useful to inform policies advocating nature-based solutions to climate change, health problems and the challenges of urbanisation.

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This Research Report looks at a broad range of urban forest-based ecosystem services and disservices and, using a literature review, links their provision with four aspects of urban forests (physical scale, physical structure and context in terms of location and proximity to people and land use and ownership). A key objective of this report is to illustrate the specific role of trees in delivering benefit to society, as opposed to delivery being assigned to green infrastructure in general, or to a particular greenspace type.

Four scale-based urban forest elements are considered: single tree, line of trees, tree cluster and woodland. The ecosystem services are grouped into provisioning, regulating and cultural, and in the main part of the report each service is considered in turn, with in most cases a table summarising the urban forest parameters that are reported in the literature to improve that service. A summary table is provided which brings together delivery indicators for urban forest ecosystem service provision. The report then considers ecosystem disservices in a similar way.

Such information will be helpful for mapping and quantifying ecosystem service delivery over a given area and for determining how and where the urban forest can be bolstered in support of ecosystem service provision, including a reduction in ecosystem disservices. To this end, synergies and trade-offs in ecosystem service delivery are also considered. By revealing which component parts of the urban forest are frequently associated with the benefit, the report can help policymakers and urban forest practitioners in Britain make informed decisions on how to improve the long-term and sustainable delivery of ecosystem services for a more resilient society.

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