Assessing the contribution of urban green spaces in green infrastructure strategy planning for urban ecosystem conditions and services

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Highlights

- A combined method of MAES and urban green space components analysis is developed.
- Urban ecosystem services and urban ecosystem conditions are mapped and co-assessed.
- A set of simple UK-specific supply rates for 6 common services is calculated.
- Scale, composition and spatial arrangement of components affect service delivery.
- Synergy of services can be stimulated by designing urban green space components.

Abstract

Maintaining ecosystem services is a key adaption option towards sustainable cities and adaptive societies in securing citizens' health and wellbeing. This research investigates the contribution of using urban green space components as the basic units in green infrastructure strategy planning for urban ecosystem conditions and services. A total of 9 types of urban green spaces are selected and delineated from the high-resolution data. A combination of the quantification method of 6 common urban ecosystem services based on urban green spaces and the MAES framework in reference to literature data is used. A case study of Cheltenham, a typical urban town in England, is studied to present the new approach for local green infrastructure strategy development for urban ecosystem conditions and respective services in improving the resilience of a city in facing global climate change. Results show that changing the composition and spatial arrangement of urban green space components, synergy or trade-off of various services can be stimulated easily. The small scale of urban green space components allows local detail planning and potential integrated planning among other urban settlements.

Keywords: urban green spaces; urban ecosystem conditions; urban ecosystem service bundles; green infrastructure; MAES; England

1 Introduction

In 2018, there was an estimation of over half of the world's population living in urban settlements while the percentage will be projected to increase to about 60% by 2030 (United Nations, 2018). It is predicted that more urbanisation processes in the current mega cities or of the newly-developing cities will happen.

However, living in these cities, more people are directly facing the consequences of the global climate change, such as continuous increase in extreme weather events, loss of land ecosystem and biodiversity as well as the respective ecosystem services (IPCC, 2019). In order to reduce the vulnerability and improve the resilience of the urban settlements, specific adaptions should be made along sustainable developments, including physical and social infrastructure (IPCC, 2018; Revi et al, 2014). Maintaining ecosystem services is one of the key adaption options to enhance the adaptive capacities of societies (IPCC, 2018). The design of policies and governance systems related to land adaptation, such as land use and integrated landscape planning, can contribute to the sustainable urban development as well as maintaining ecosystem service (IPCC, 2019).

Ecosystem services (ES) are defined as "the contributions of ecosystem structure and function (in combination with other inputs) to human well-being" (Burkhard and Maes 2017, 23). Good qualities of living of human being are highly relied on the functions of ecosystem i.e. the ES provided by the nature to human society (Burkhard and Maes, 2017), while the provision and capacity of the ES by ecosystems mostly depend on their condition (Maes et al., 2018). Therefore, the assessment of ecosystem conditions (EC) along with mapping and quantifying of the ES in biophysical, social and economic manners with various spatial scales would be a potential policy and decision-making tool in human societal development (Burkhard et al., 2018; Burkhard and Maes, 2017; Pulighe et al, 2016) including the urban green infrastructure (GI) approach or strategy developments (Benedict and McMahon, 2006; Ramyar et al., 2020; Ramyar and Zarghami, 2017; Weber et al., 2006).

Focusing on the urban scale, urban green spaces are popular elements in the study related to urban ES. Several studies have used the ES assessment method in explaining the importance or contribution of urban green spaces and green infrastructure (GI) (Belmeziti, Cherqui, & Kaufmann, 2018; Chang et al., 2017; Derkzen, van Teeffelen, & Verburg, 2015; Gren and Andersson (2018). Recently, Ronchi et al. (2020) have investigated the necessity to link ES, green infrastructure and nature-based solutions for planning purposes.

However, the above studies have seldom addressed the EC as well as the relationship of ES and EC in GI planning (Kourdounouli & Jönsson, 2020). Also, the result of these studies usually cannot be easily compared because of the differences in research methodologies and parameters.

Regarding the quantitative study of ES and EC, a coherent assessment framework Mapping and Assessment of Ecosystems and their Services (MAES) for all European Union (EU) members is highlighted in the EU Biodiversity Strategy to 2020 (European Commission, 2019). Though there are 3 levels of scale from national, regional to local in the framework, they are new to the EU members and the studies in local scale are still limited (Maes et al., 2016b; Nedkov et al., 2016). Local urban EC and ES co-mapping and assessment seem to have received less attention in the research field because of the relatively smaller size and lower value of the urban ecosystems (Davies et al., 2011; Derkzen et al., 2015; Russo et al., 2016). In fact, it is vital to evaluate the urban EC and ES provision in local areas where most populations live and have their everyday activities (Davies et al., 2011; Roussel et al., 2017; United Nations, 2018). Also, a bundle or stacked ES should be quantified and assessed in a local scale in order to be useful for policy and planning purposes (Derkzen et al., 2015; Russo et al., 2016).

Therefore, using a set of urban green space types as the basic elements in mapping and quantifying a stack of urban ES and EC is a potential method to contribute the GI strategy planning. By exploring the new approach of local GI network development and strategy establishment, urban EC and respective urban ES as well as the resilience of a city would be maintained or even enhanced in facing global climate change.

In this study, the paper assesses the contribution of using urban green space (UGS) as the basic components in GI strategy planning for urban EC and ES. A total of 9 types of UGS components are delineated from the high-resolution data readily available online in GIS environment. Then they are used to assess and quantify the urban EC and ES in reference to the literature data. The urban EC and ES are mapped and analysed in accordance to the framework MAES. A case study of Cheltenham, a typical urban town in Gloucestershire, England, is used to present the possibility of GI implementation planning based on UGS components.

A combination of the quantification method of a bundle of urban ES based on UGS by Derkzen. et al. (2015) and MAES framework by Burkhard et al. (2018); Maes et al.(2016b) and Maes et al. (2018) is used in this study. A new UGS type, agricultural land, are added to enhance the comprehensiveness by including the peri-urban area. A set of simplified common EC and ES indicators are selected for respective assessment. Besides the urban ES, urban EC is also taken into analysis and evaluation in local GI strategy planning based on UGS.

2 Materials and methods

2.1 Study area

Cheltenham Borough, which is based on the Regency town of Cheltenham, is one of the major sub-regional centres for employment and urban settlement in Gloucestershire (Figure 1). (Cheltenham Borough Council, 2006; Cheltenham Borough Council, 2020). It had a population of 117,090 in 2018 and covers an area of 4,680 hectares, geographically lying between the Cotswolds and the vale of the River Severn located in the southwest England (1.8994° N, 2.0783° W) (Cheltenham Borough Council, 2006; Office for National Statistics, 2019). The urban town, surrounded by areas of countryside, is relatively flat and gently sloping down to the River Chelt (Cheltenham Borough Council, 2006). It experiences average annual minimum and maximum temperature of 22°C and 2°C respectively while receives more than 1,600 hr of sunshine and 800-900 mm of rainfall annually (Met Office, 2016).

Cheltenham Borough consists of 18 wards with 17% designated area of Green Belt and 22% area of the Cotswolds Area of Outstanding Natural Beauty (AONB) which encompass the development pattern (Cheltenham Borough Council, 2006).

Cheltenham is selected as a case study area because of its

- simple urban structure; and
- complete profile of land use ranging from urban to rural environment

to demonstrate the use of MAES in the mapping and assessing urban EC and ES. Administrative boundary of Cheltenham Borough is used in the study because it is the most relevant to the development decision-making process by the local council (Holt et al., 2015).

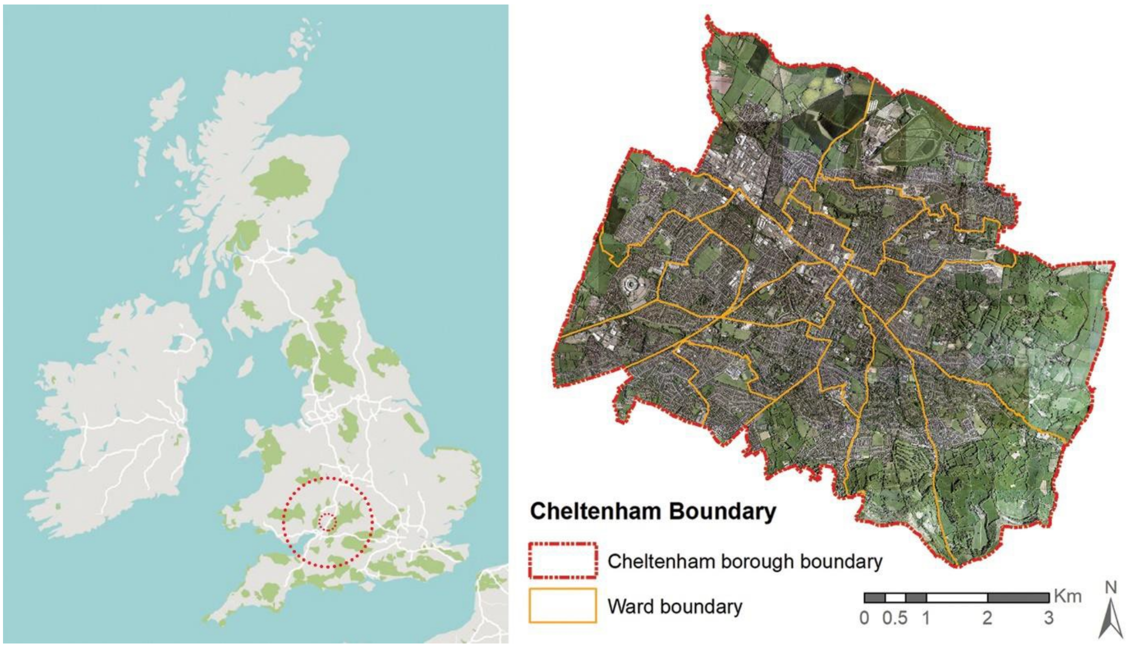


Figure 1 Location of Cheltenham and Boundary of Cheltenham Borough. Source: Getmapping High Resolution (25cm) Vertical Aerial Imagery (2018)

2.2 Operational framework for the mapping and assessment of ecosystems and their services (MAES)

In this paper, MAES is used (Burkhard et al., 2018; Maes et al., 2016b; Maes et al., 2018) while urban ecosystem conditions (UEC) and urban ecosystem services (UES) are focused (Figure 2).

Data source & data processing

High-resolution open data sources to which the public and policy-makers of individual councils would access easily are used in this study. Details of data used in delineation, mapping and quantification of urban ecosystem types, UEC and UES are listed in Appendix I. All data is processed through the *Geographical Information Systems (GIS) software ESRI ArcMap 10.5.1.*

Step 1: Question and theme identification

As stated in the objective, the theme of the case study is to support and evaluate the current GI strategies by the result from MAES.

Step 2-3: Identification and mapping of urban ecosystem types

The types of urban ecosystem of Cheltenham are classified in accordance to the *CORINE Land Cover Maps 2018* (2020a) within the administrative boundary of Cheltenham Borough (Burkhard et al., 2009; Burkhard et al., 2012; Burkhard et al., 2018; Zhang & Ramírez, 2019). 10 major classes of urban ecosystem types are identified (Figure 3).

Since a single discontinuous urban fabric patch covers a majority of the area of Cheltenham, it is further divided into 18 sub-areas according to the ward boundary in order to allow in- depth comparisons of UEC and UES. Other classes are delineated in respective to their geographical locations.

In total, 45 urban ecosystem sub-areas (Appendix II) are mapped by ArcMap in the form of a polygon shapefile and the corresponding information is stored in the attribute table.

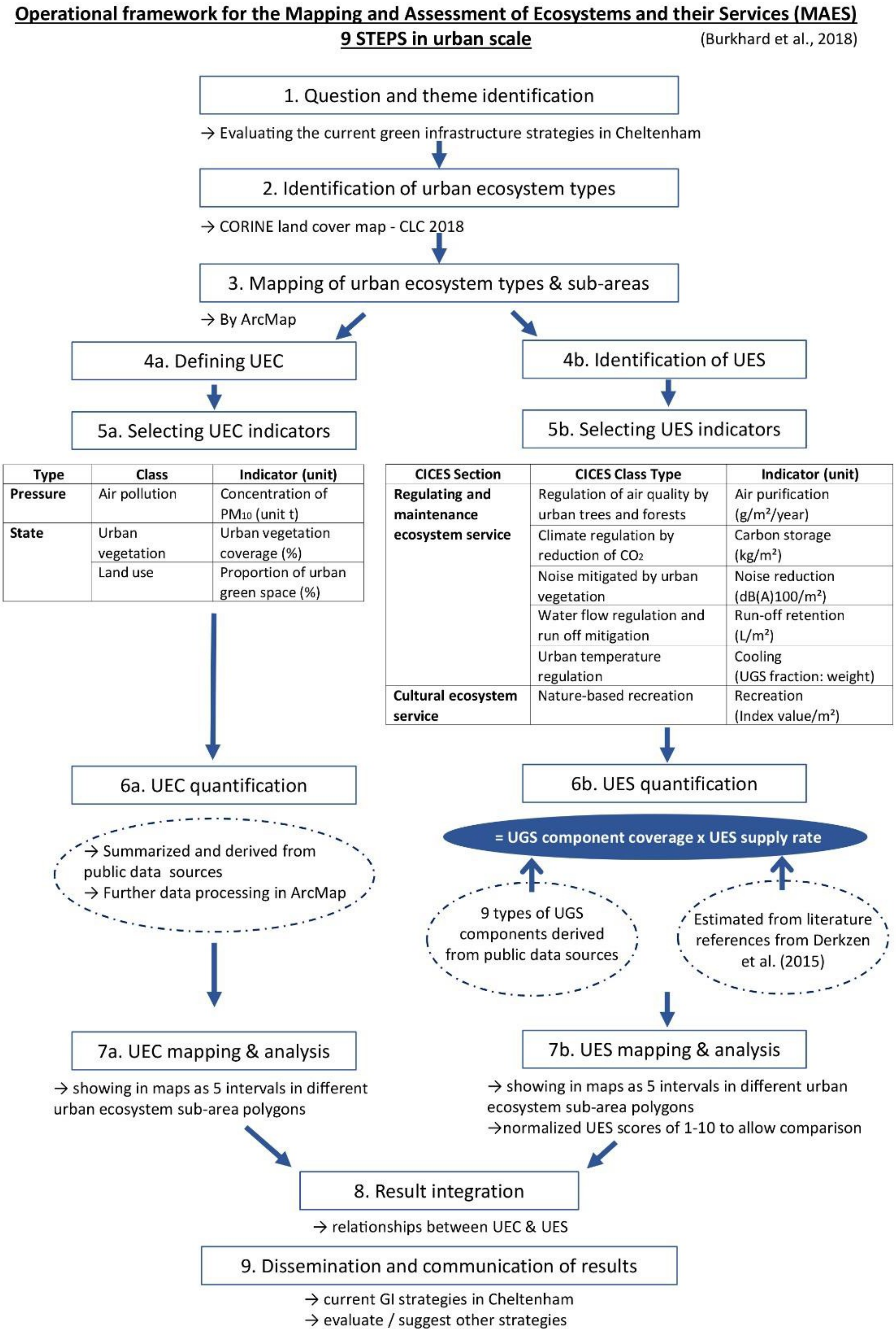


Figure 2 Research flow of MAES

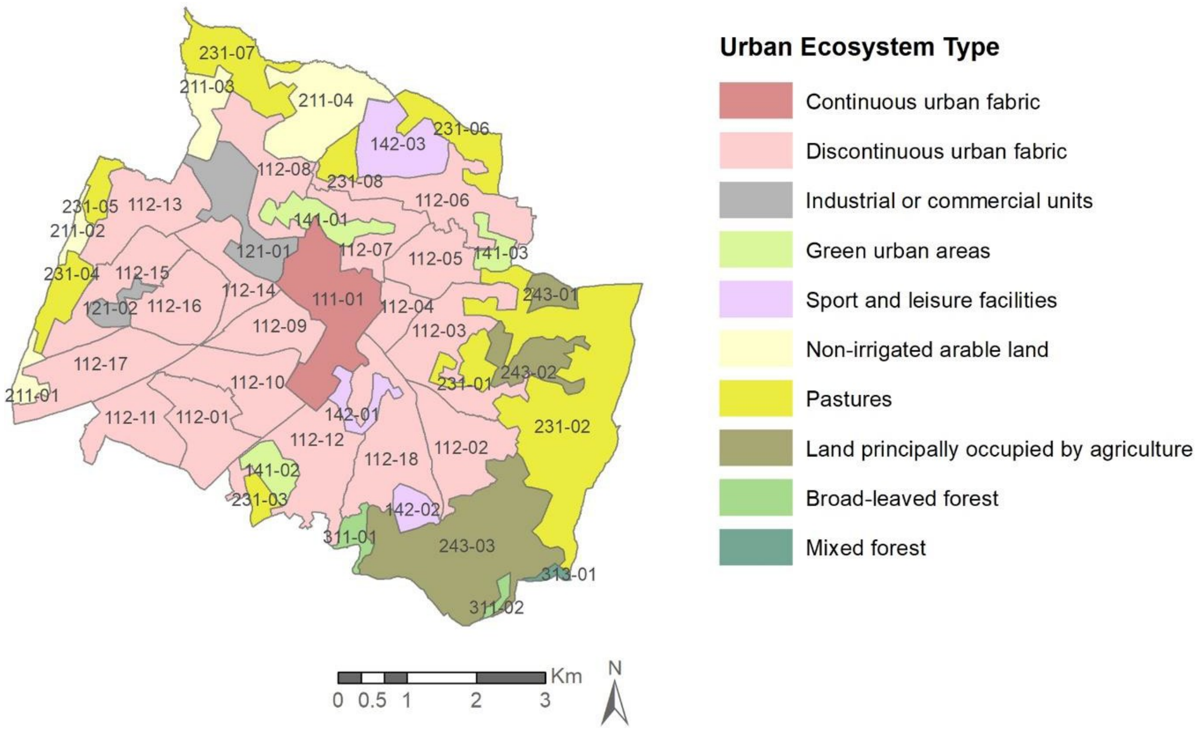


Figure 3 Urban ecosystem types of Cheltenham

Step 4a: Defining Urban ecosystem condition (UEC) & Step 5a: selecting indicators

UEC is defined as a description of the structure or functioning of an urban ecosystem respective to some predefined criteria and it is highly related to the capacity of an urban ecosystem to provide corresponding UES (Burkhard et al., 2018). Therefore, indicators are selected and quantified in order to assess the UEC within the profile of the built and green infrastructure in an urban area (Maes et al., 2016b).

1 pressure indicator, the concentration of PM_{10} (unit/t) is used to access the UEC class of air pollution. 2 state indicators, urban vegetation coverage (%) and proportion of urban green space (%) are chosen to define the UEC classes of urban vegetation and land use respectively.

Indicators such as population density and density of road network are not used because they usually show high values within the urban ecosystem and the measurement becomes less significant than that in the natural ecosystem (Maes et al., 2016b).

Step 6a: UEC Indicator quantification

Air pollution

The data of the concentration of PM_{10} (particulate matters ≤10μm) (unit/t) is obtained from the UK NAEI Emissions Interactive Map 2017 (2019) online. The 1km x 1km resolution data is imported into ArcMap and normalised by the area of corresponding urban ecosystem sub-areas.

Urban vegetation

Copernicus Sentinel 2 Colour Infrared Satellite Imagery (2020b) of Cheltenham is used to calculate the urban vegetation coverage (%) for each urban ecosystem sub-area. The vegetation coverage is extracted by the Normalised Difference Vegetation Index (NDVI) analysis in ArcMap.

NDVI is one of the major vegetation indices used in remote sensing assessment and monitoring of vegetation cover globally over the last 30 years (Huete and Liu, 1994; Jiang et al., 2006; Leprieur et al., 2000). It normalises the ratio between the high reflectivity of near infrared wavelengths with the low reflectivity of red wavelengths (high absorption for photosynthesis) defined as the following equation:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

where NIR and RED represent the spectral reflectance of near infrared and red wavelength respectively (Jiang et al., 2006; Sentinel-Hub, 2020). NDVI ranges from -1 to +1. The more positive the value, the denser and healthier the vegetation is. In this study, the grading of vegetation cover adopted are non-vegetation (NDVI<0.4) and vegetation (NDVI≥0.4) after corresponding adjustment specific to Cheltenham (Peng et al., 2019). The vegetation cover is then extracted in the form of a polygon shapefile while the coverage (%) is calculated as vegetation cover in each sub-area normalised by the corresponding area.

Land use

The urban green space is defined according to the categories listed in the *UK Ordnance Survey OS MasterMap Greenspace layer* (2019), which contains 18 types of urban green spaces. 2 categories of Private Garden and Land Use Changing are excluded since they are usually not accessible by the public or under planning process respectively.

The urban green space polygons are then distributed into the corresponding urban ecosystem sub-areas while the proportion (%) is calculated as urban green space cover in each sub-area normalised by the corresponding area.

Step 7a: UEC Mapping & analysis

The UEC maps are presented in the ArcMap layer as polygon shape files. Equal interval statistic method is used to divide each UEC indicator value into five intervals while the polygons are presented from light to dark colour.

Step 4b: Identification of Urban ecosystem service (UES) & Step 5b: selecting indicators

UES is divided into 3 main categories according to CICES including provisioning, regulation & maintenance and cultural ES (EEA, 2020; Haines-Young and Potschin, 2013; Maes et al., 2016a).

In this study, 6 CICES UES classes with their corresponding indicators are selected to map and assess in reference to Derkzen et al. (2015) and Maes et al. (2016b) (Table 1). These 6 UES are the most common and more relevant to the health and well-being of people living in urban areas (Derkzen et al., 2015; Holt et al., 2015; Tratalos et al., 2007; Whitford et al., 2001).

Step 6b: UES quantification

The quantification of UES in this study is following the methodology proposed by Derkzen et al. (2015). 9 types of urban green space (UGS) components (Table 2) are used as the basic units to calculate and quantify the UES based on the review of the literature data and estimation methods by Derkzen et al. (2015).

UGS component & UES supply rate

The information of UGS components of woodland, herbaceous vegetation, private garden, water body, agricultural land and others are retrieved from *Ordnance Survey GB Map* (2019a,b,&c) online while that of tree, tall shrub and short shrub are mapped as polygon shape files by visual interpretation using high-resolution orthophotos, *Google Earth* and *Google Street View* in *ArcMap* (Appendix II).

UES supply rates per m^2 of UGS components are given out after further literature review and adjustment on previous data considering the UK situation (Table 3). More details would be referenced to Appendix III and Derkzen et al. (2015).

Air purification

The air purification UES here is defined as the g PM_{10} captured per m^2 of UGS per year (g/m^2/year). That of the UGS is double counted within the 50m buffer zone around major traffic roads in order to explain the effect on the PM_{10} concentration (Cavanagh et al., 2009; McPherson et al., 2011; Tallis et al., 2011; Vos et al., 2013).

The rates for tree and woodland are based on 2 UK studies (McDonald et al. 2007; Tallis et al. 2011). Because of the absence of other UK studies, that for shrubs is calculated in reference to other cities with the adjustment respective to the tree and woodland values from the UK (Baumgardner et al. 2012; Escobedo and Nowak 2009). The herbaceous value is assumed to be 1/3 of the rate provided by woodland (Fowler et al., 2004).

Carbon storage

The carbon storage UES here is defined as the kg carbon stored per m^2 of UGS (kg/m^2). The supply rate of each UGS is based on a UK study of aboveground carbon storage at a city-wide scale by Davies et al. (2011) using field surveys and allometric equations. The rate for tree and woodland is assumed to be the same in the calculation. The value of agricultural land is referenced from the review of the UK land use and soil carbon sequestration by Ostle et al. (2009).

Noise reduction

The noise reduction UES here is defined as the physical capacity to reduce environmental noise dB(A) per $100m^2$ of UGS ($dB(A)100/m^2$). In this study, analysis focuses on traffic noise. The capacity is only counted within the 50m buffer zone created around main roads and railways since most of the sound wave would be blocked by the dense urban structures beyond that distance (Fang and Ling, 2003; Samara and Tsitsoni, 2011; Van Renterghem et al., 2012).

The noise reduction UES supply rates for tree, i.e. the single row of tree or individual tree, and private garden, which is usually hidden behind building blocks, are set to be zero because they are ineffective in reducing noise (Fang and Ling, 2003; Samara and Tsitsoni, 2011; Van Renterghem et al., 2012).

Run-off retention

The run-off retention UES here is defined as the liter run-off retention per m^2 of UGS (L/m^2). In this study, run-off interception and infiltration by vegetation and water bodies are estimated in accordance to the technique adapted from 2 UK studies, Tratalos et al. (2007) and Whitford et al. (2001) whose studies are based on that by Pandit and Gopalakrishan (1996) originally from the Soil Conservation Service (SCS) (1972). The equation for calculating surface run-off (Pe):

$$Pe = \frac{(P - 0.2S)^2}{P + 0.8S}$$

where P denotes the precipitation and S the maximum potential retention of catchment of which S is given by:

$$S = \frac{2540}{CN} - 25.4$$

where CN represents the curve number calculated by the SCS for each combination of land cover and soil type. CNs are referenced to that used in Tratalos et al. (2007) except that the CN for agricultural land is calculated according to the USDA (1986), the mean CN over the row crops and small grain with straight row and crop residue cover treatment.

A common average run-off occurrence in the UK cities from a 12mm rainfall event is adopted while the run-off coefficient Q is calculated as Pe/P; and the run-off retention is given out by P X Q (Tratalos et al., 2007; Whitford et al., 2001).

Cooling

The cooling UES here is defined as the relative cooling potential per m^2 UGS surface area compared to each other (UGS fraction: weight). In this study, the UES supply rate is given out based on the weighting developed by Derkzen et al. (2015) which only considers the cooling contributed by vegetation via shading and evapotranspiration; therefore, the rate of water body is set to be zero. Trees, woodland and shrub surface area are given full potential on cooling while herbaceous, private garden and others are weighted 0.5 because of their primary composition of lawns (Smith et al. 2005; Tratalos et al. 2007) which gives a lower cooling potential (Armson et al., 2012; Skelhorn et al., 2014). Weighting for agricultural land is calculated as half of the mean over shrub and herbaceous due to the annual crop harvesting.

Recreation

The recreation UES here is defined as the recreation index value per m^2 of UGS (Index value/m^2) calculated by the recreation index developed by Derkzen et al. (2015) after literature review and related generalization of people's preference on different UGS.

The rate is expressed as the mean value of the Landscape and Naturalness score of UGS while that in the public park or garden area is calculated double because of the synergy effect of the various combinations of most UGS in an open space (Derkzen et al., 2015).

Step 7b: UES Mapping & analysis

Individual UES is calculated by the sum of product of subtotal area of each UGS with the corresponding UES supply rate as listed in Table 5 (Derkzen et al., 2015). Then the UES supplied by each urban ecosystem is normalised by the area for comparison (Derkzen et al., 2015).

Equal interval statistic method is used to divide each UES indicator value into five intervals while the polygons are presented from light (minimum) to dark (maximum) colour corresponding to that in the previous mapping (Burkhard et al., 2012; Burkhard and Maes, 2017; Derkzen et al., 2015). The individual UES information is stored in attribute tables and mapped in the *ArcMap* map layers as polygon shape files.

In order to further identify and compare the UES performance of different urban ecosystems and sub-areas, the actual amounts of each UES supply are normalised on a scale of score of 0 (minimum) -10 (maximum) and shown on stacked bars and bar charts with the UGS coverage. Maximum overall UES supply score is 60, which consists of 10 each for the 6 UES studied.

Step 8 - 9: Result integration & communication- local green infrastructure strategy evaluation and suggestion

The UEC and UES are analysed to evaluate the UES capacities provided by individual urban ecosystem sub-areas which have different UEC (Burkhard et al., 2018). The results are finally overlaying with the current Cheltenham GI strategic plan (JCS Local Planning Authorities, 2014) to analyse if there is any further support or improvement.

3 Results

3.1 UEC & urban ecosystem

In this study, the UEC of Cheltenham are studied in terms of air PM_{10} concentration (pressure), vegetation coverage (state) and proportion of urban green space (state) (Figure 4).

In terms of air PM_{10} concentration, the pressure decreases from the urban core to the peripheral rural areas, especially the northern and eastern boundary. Higher PM_{10} concentration in Inner urban part (111, 112, 121) (Appendix II) would be explained by the higher density of traffic networks and more industrial pollution sources, such as the publishing industry. On the contrary, the northern part of Cheltenham comprises mainly agricultural lands while eastern part belongs to the Cotswold AONB (211, 231, 243); therefore, the PM_{10} pressure on these urban ecosystems is smaller.

Vegetation coverage increases from the urban core to the peripheral rural areas, especially the northern and eastern boundary as well as some areas in the far west. Lower vegetation coverage in inner urban part (111, 112, 121) is due to the dense urban structures and road networks while higher coverage in the peripheral area (211, 231, 243) is contributed by the land for agriculture and pasture. Also, some urban green spaces (141) and leisure areas (142) provide a good vegetation cover to the inner urban part.

For the land use condition of the urban ecosystems, proportion of urban green space, which serves for most the public, shows a more scattered pattern across Cheltenham. The highest proportions of urban green space are observed in urban green space (141) and leisure area (142) across the town. A moderate proportion in some discontinuous urban fabric areas (112) would be explained by the amounts of small parks or gardens and roadside plantations in the residential area. Urban core (111, 121) has the lowest proportion as most lands are occupied by buildings or commercial and industrial activities. Low proportion is also found in the peripheral areas (211, 231, 243) since most agricultural lands and pasture areas are not accessible by the public.

3.2 UGS & UES

Individual UES capacity

The individual UES capacity here is expressed in terms of the UES supply rate of each UGS component. Different UGS components provide various UES capacities while none of them outperform each other (Table 4).

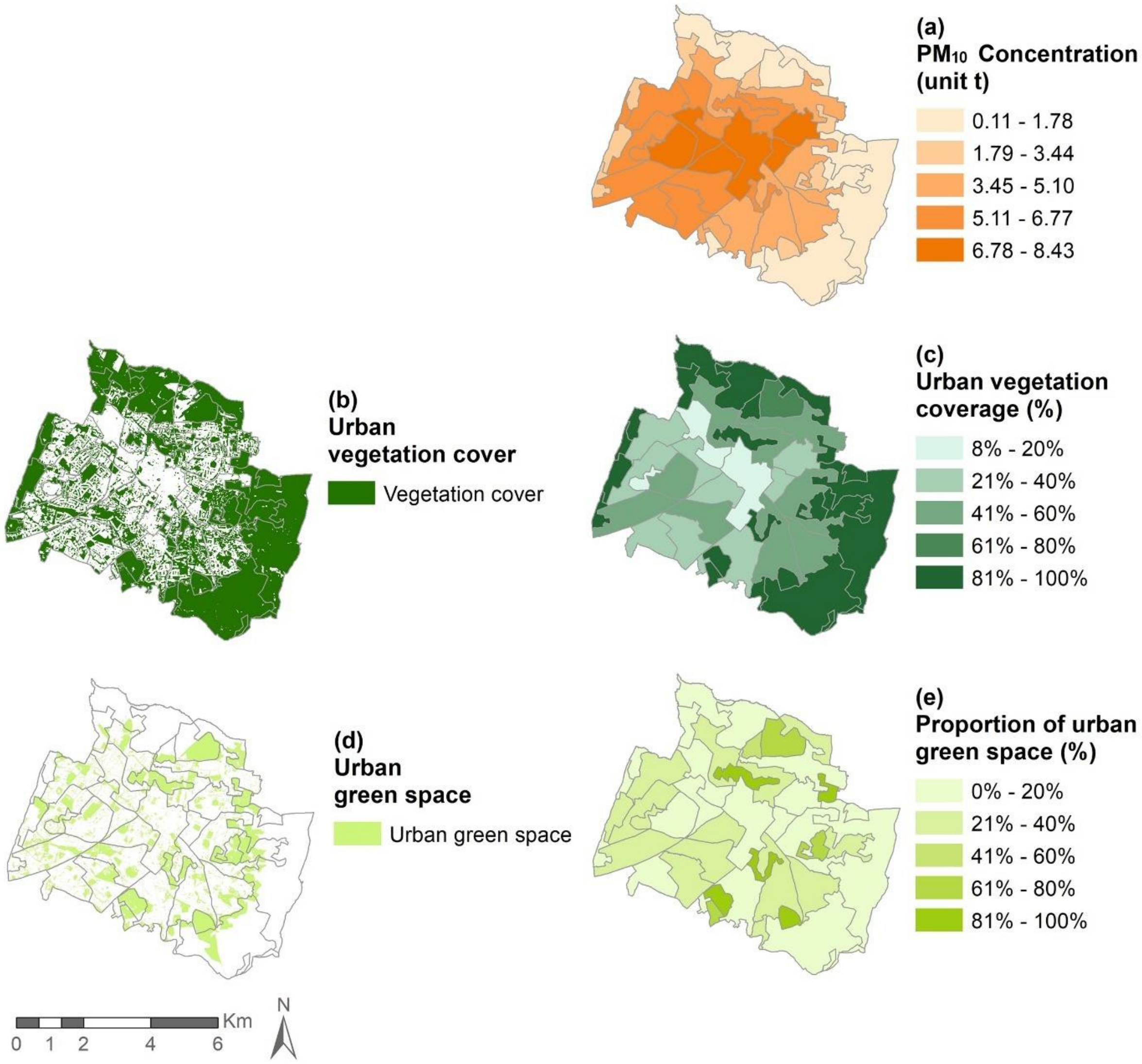
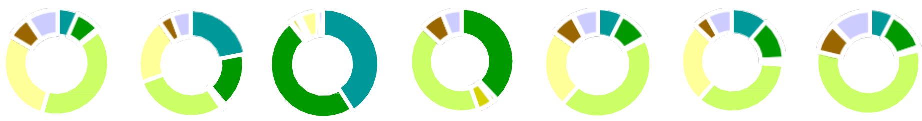


Figure 4a-e UEC for different urban ecosystem sub-areas in Cheltenham



Overall, trees and woodlands are effective UES providers followed by shrubs among all the UGS components. Trees and woodlands share the highest UES capacities in air purification, carbon storage and cooling as well as the second highest in run-off retention. Nevertheless, tall shrubs provide the best noise reduction capacity while an individual tree has no capacity for that. Water bodies also have an excellent capacity in run-off retention although they contribute none for most of the other UES.

Herbaceous vegetation also plays a moderate role in run-off retention and recreation but much less important in the other UES. Private gardens and others share similar UES capacities except for noise reduction and recreation because of the privacy of the garden comparing to the others. Agricultural land seems to be a less effective UES provider than the others as its vegetation types consist of short shrubs and herbaceous vegetation with annual harvesting characteristics.

UGS coverage

The total amount of UGS coverage mapped in this study is 3,756.39 ha. Herbaceous vegetation (mostly grassland) and private gardens comprise the majority of UGS of 39.81% and 29.08% respectively. Trees, woodlands, agricultural lands and others composes less than 10% each while shrubs and water bodies even only comprise less than 1% each.

Total amount of UES

The amounts of UES provided by different urban ecosystem sub-areas may depend on 3 factors:

1. the individual UES capacity of UGS component, i.e. the UES supply rate;
2. the UGS coverage in urban ecosystem sub-areas; and
3. the spatial patterns of UGS and urban setting

In the case of Cheltenham, trees, woodlands, herbaceous vegetation and private gardens are good UES providers considering the above 3 factors.

For trees, they contribute the second most in carbon storage (41.01%) and air purification (21.91%) although they comprise only 6.32% of UGS overall. Similar to trees, woodlands provide most capacity for carbon storage (48.20%) and second most to noise reduction (37.91%) with the UGS coverage of only 7.43%. It is because trees and woodlands both share higher capacities in carbon storage and air purification than the other UGS (Table3).

Moreover, herbaceous vegetation contributes the most in UES, especially recreation (57.60%) and run-off retention (43.81%) due to their largest UGS coverage except for the carbon storage. Similar to herbaceous vegetation, private gardens also provide the second most in cooling (25.81%) and run-off retention (23.54%) with their second largest UGS coverage.

For shrubs and water bodies, the abundance of them in Cheltenham is the least so they only contribute very little to UES though they have moderate UES capacities. Agricultural lands and others contribute much less as they both have relatively lower UES capacity and less coverage in urban areas.

Spatial characteristic of UGS & urban setting

Spatial pattern of UGS also affects the total UES (Andersson et al., 2014; Derkzen et al., 2015) especially on those pollution regulating UES, i.e. air purification and noise reduction. For pollution regulating UES, the amount of services calculated mainly depends on the proximity or availability of the UGS to the pollution sources.

In this study, the air purification capacity of UGS is double counted if they fall into the 50m buffer zone of the traffic road which is assumed to be the major source of PM_{10} in air pollution (Figure 5). In the case of noise reduction, only the capacity of the UGS within the 50m buffer zone is calculated. Long and continuous UGS pattern would be the most benefit to the services (Derkzen et al., 2015). Therefore, the spatial distribution of the UGS is more important than the sole amount of UGS within each urban ecosystem sub-area. It makes a difference from the calculation of other general regulating UES, such as carbon storage, run- off retention and cooling, which depend on the amount of UGS rather than their sizes, shapes or patterns.

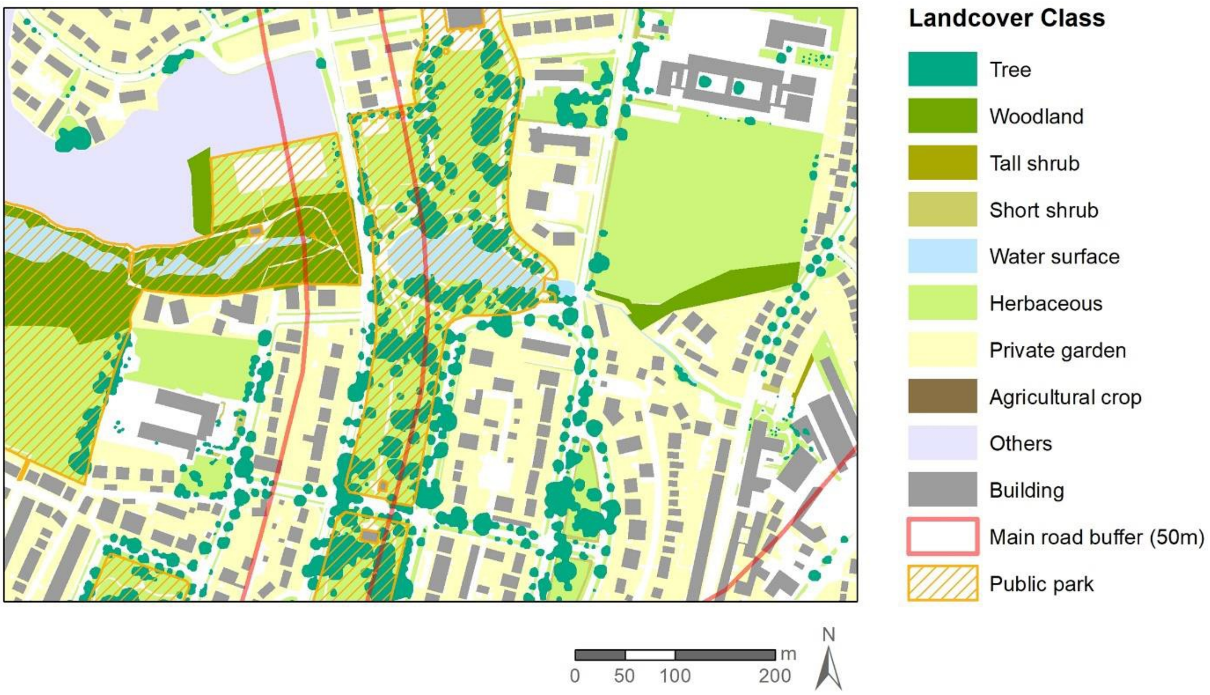


Figure 5 Detailed map illustrating the distribution of UGS components in Cheltenham

On the other hand, urban setting is another factor affecting the UES supply calculation. For example, some urban ecosystem sub-areas contribute none to noise reduction as there are even no pollution sources, i.e. main traffic roads, within the area rather than they are lacking the amount of UGS. The UGS would provide the services, i.e. the maximum capacity, as long as there is a need for that rather than only the service they are actually providing at the moment.

3.3 **UGS, UES & urban ecosystem**

Major urban ecosystems & their UES

The UGS and UES supply from each area show relationship with the urban ecosystem types. The UGS and UES supply increases towards the peripheral area of Cheltenham where most lands for agriculture, pasture and forest locate (Figure 6). Less UGS and UES supply are shown in the core of Cheltenham where the town and commercial centre are. Some green urban spaces and leisure facilities provide greater extent of UGS & UES supply in the middle of the urban fabric.

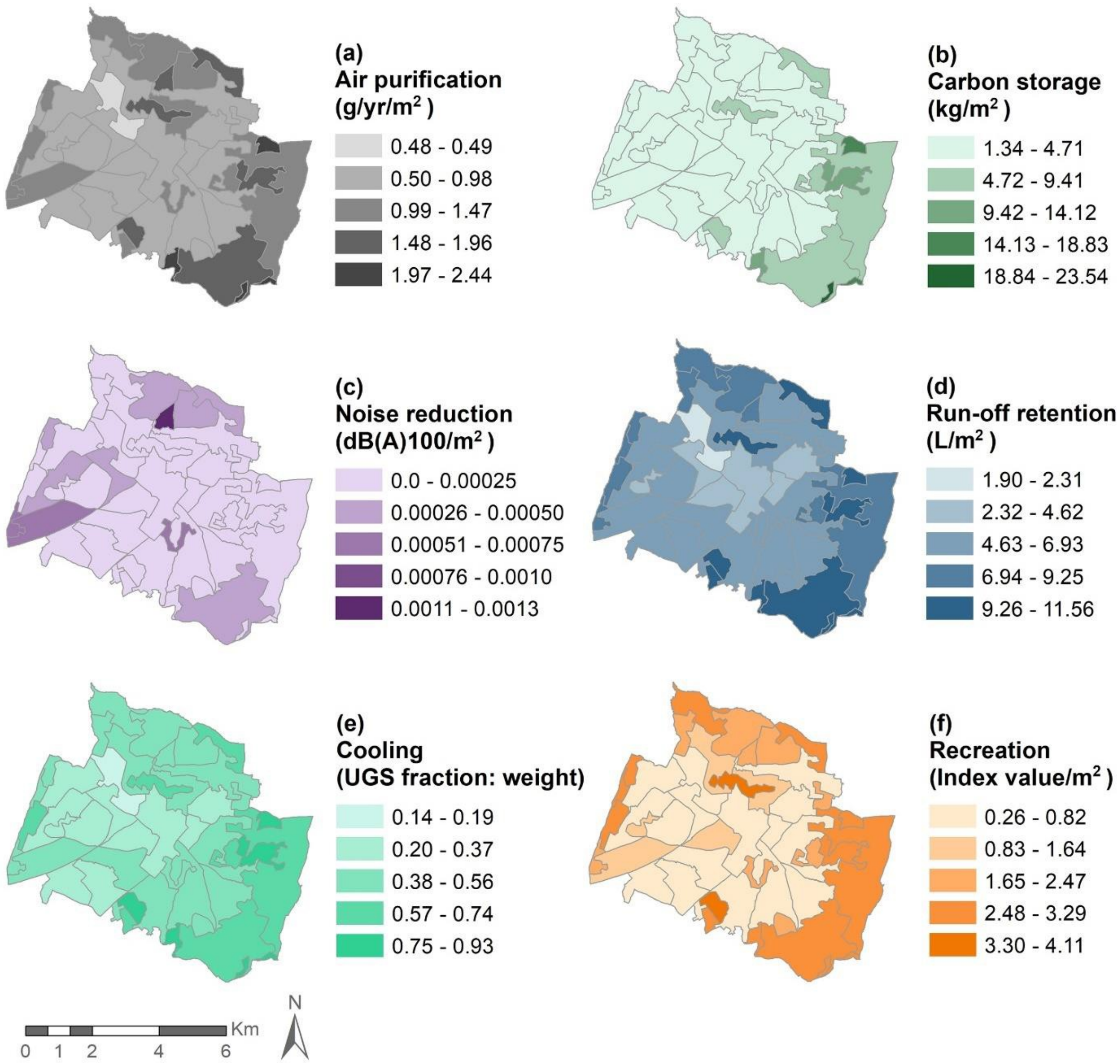


Figure 6a-f 6 UES supplies by different urban ecosystem sub-areas in Cheltenham

Overall, urban ecosystem types mixed forest (313) and broad-leaved forest (311) (Appendix II) score the highest and second highest for overall UES supply followed by agricultural land (243), green urban space (141) and pasture (231) (Figure 7). Continuous urban fabric (111), industrial or commercial units (121) and discontinuous urban fabric (112) score the lowest and second lowest.

And the percentage coverage of UGS shows a similar pattern (313: 121.58% vs 121: 25.34%) with the UES score except for that of green urban space is ranked as the second highest UGS coverage (119.26%). Some urban ecosystem types have UGS coverage more than 100% because overlapping of UGS is allowed. For example, the grass or shrub growing under the tree canopy probably contributes to the UES too.

The distributions of individual UES scores for mixed forest and broad-leaved forest are quite even except for the noise reduction because of the absence of pollution sources in the two ecosystem types. For agricultural land, pasture, non-irrigated arable land (211), sport and leisure facilities (142) and green urban space, lower UES scores in carbon storage and noise pollution are observed. It may be caused by the change of UGS composition in the urban ecosystem type, such as fewer trees but more herbaceous vegetation resulting in a different capacity of UES supply.

With various compositions of UGS, they may lead to different results in overall UES score in spite of the similar percentage UGS coverage, i.e. 313 vs 141. It also indicates the effectiveness of the UGS composition within an urban ecosystem type in providing different UES. For example, 111 vs 121, although the UGS percentage coverage of 121 is lower than that of 111, 121 shares the same UES score with 111.

Urban ecosystem sub-areas & their UES

For individual urban ecosystem sub-areas (Appendix II), 311-02, a broad-leaved forest, and 313-01, a mixed forest, which locate in the peripheral southeast area of Cheltenham, score the highest (46/60) and second highest (45/60) overall UES supply respectively (Figure 8 & 9). On the contrary, 121-01, the industrial area, and 111-01, the town centre area, score the lowest (11/60) and second lowest (13/60) overall UES supply respectively because of the low UGS coverage (121-01: 22.97% and 111-01: 34.44%). Nonetheless, 141-02, a green area in the south peripheral area of Cheltenham and 313-01 have the highest UGS coverage of 135.92% and 121.58% respectively.

The 18 discontinuous urban fabric sub-areas show similar pattern in overall UES supply score ranging from 112-04 (All Staints Ward): 14/60 to 112-17 (Benhall and the Reddings Ward): 25/60 while the UGS coverage ranges from 112-09 (Lansdown Ward): 59.66% to 112-08 (Swindon Village Ward): 75.28%. It may be explained by the similar urban setting across the discontinuous urban fabric in Cheltenham.

The UES of carbon storage, noise reduction and recreation of most discontinuous urban fabric ecosystems score lower than that of the air purification, run-off retention and cooling so forming an uneven distribution of UES supply. It may be caused by the higher percentage of private garden and herbaceous vegetation cover than that of the tree, woodland or shrub in the urban fabric ecosystems.

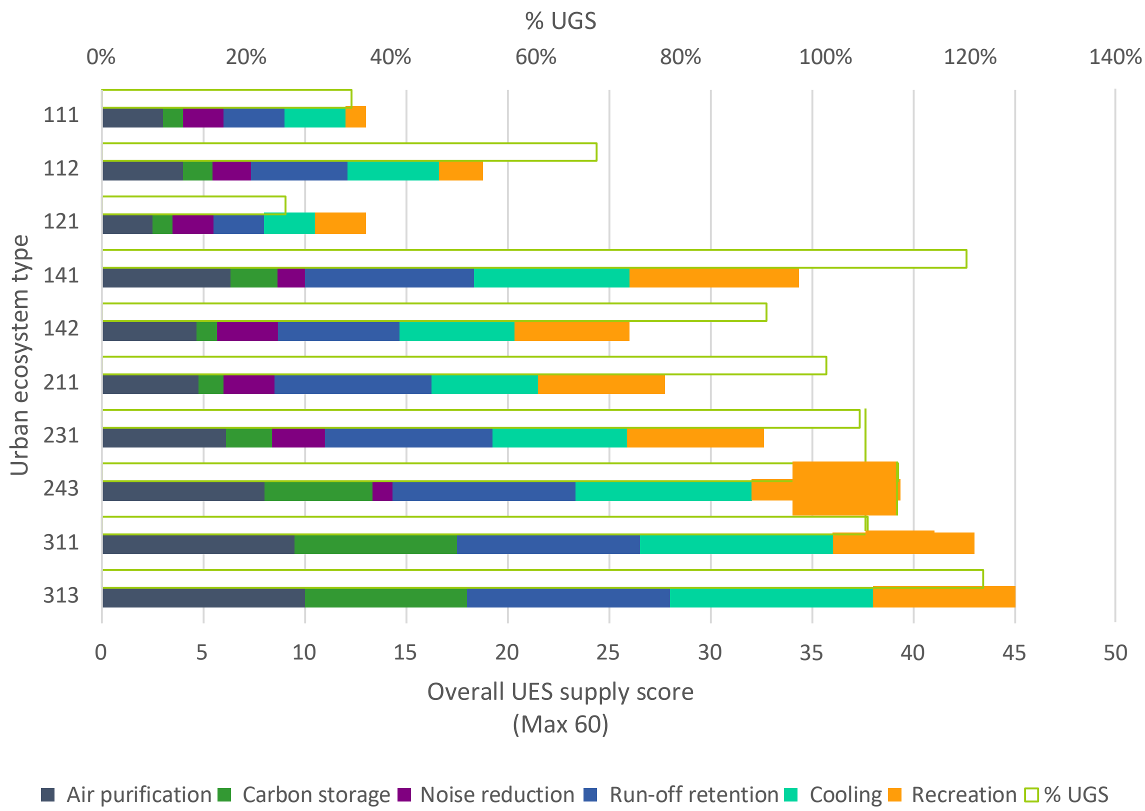


Figure 7 Overall UES supply score & % UGS coverage of different urban ecosystem types in Cheltenham (Descriptions for urban ecosystem types please refer to Appendix II)

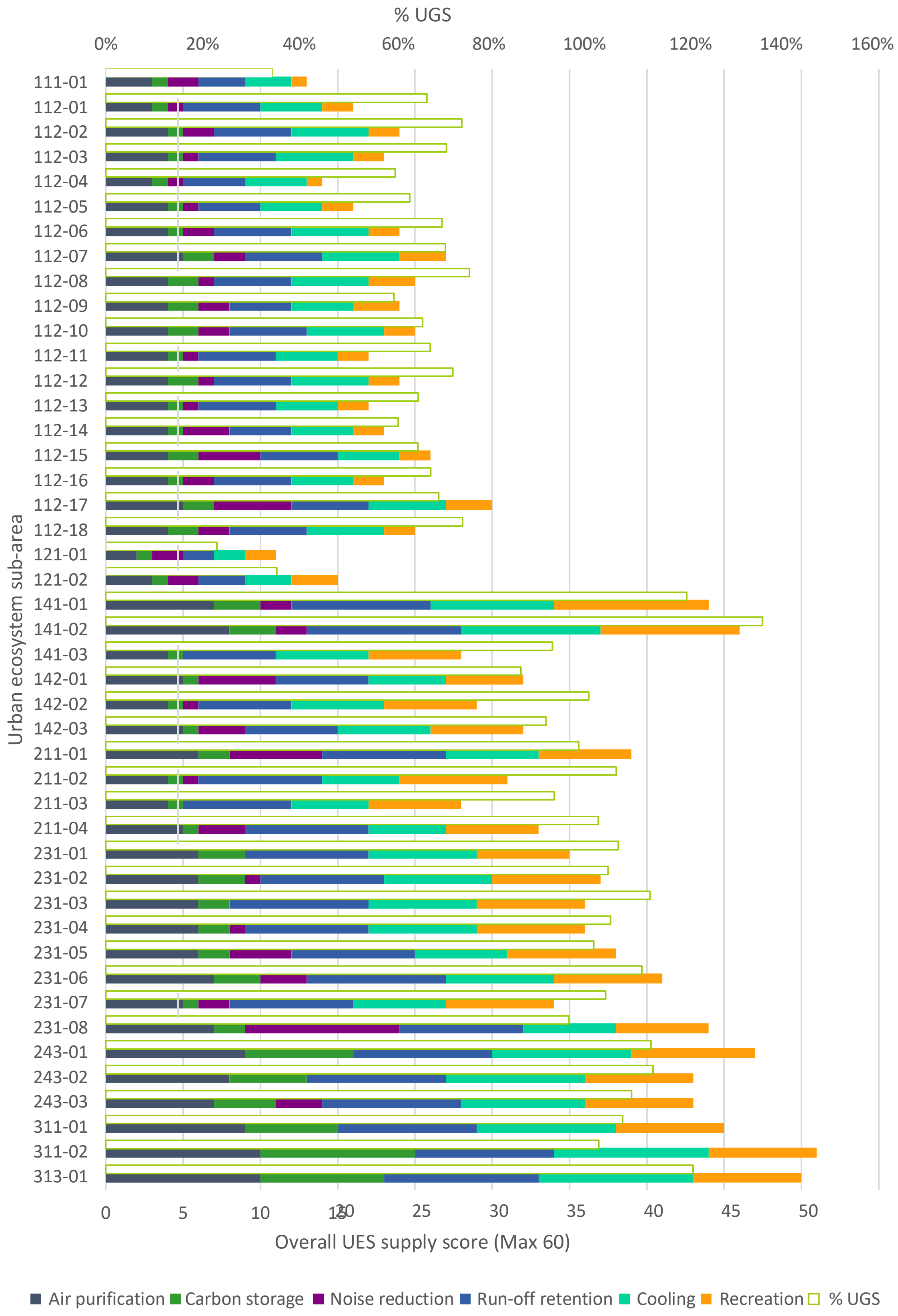


Figure 8 Overall UES supply score & % UGS coverage of different urban ecosystem sub- areas in Cheltenham (Descriptions for urban ecosystem sub-areas please refer to Appendix II)

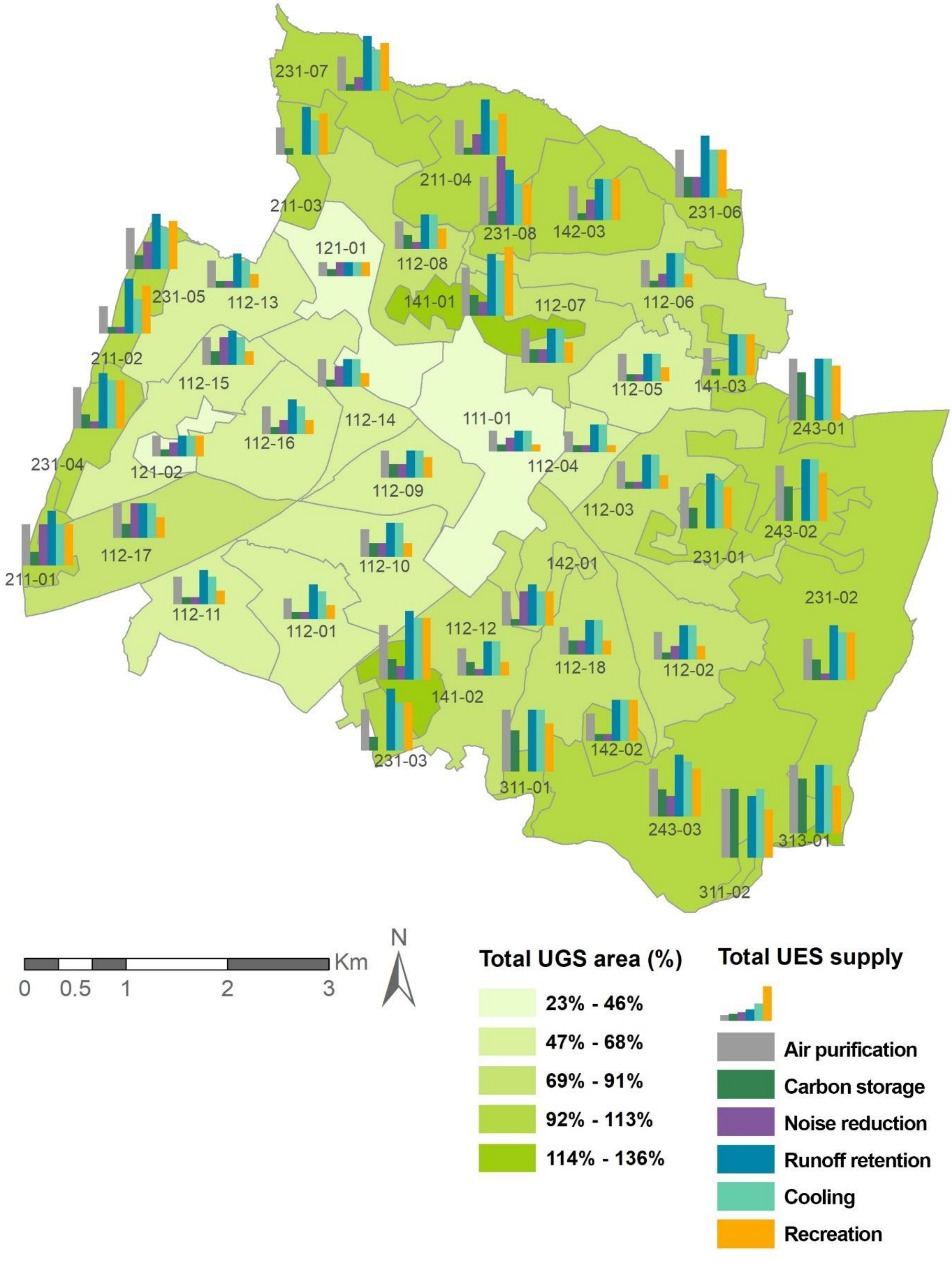


Figure 9 Map showing spatial pattern of overall UES supply & % UGS coverage of different urban ecosystem sub-areas in Cheltenham

4 Discussion

4.1 UEC & UES: Case study in Cheltenham

UES demand vs UES supply

For the pressure condition of the PM_{10} concentration, it is more likely to indicate the quality of urban environment, i.e. the people's well-being, and imply the demand for the UES of air quality regulation instead of the supply of the UES. When comparing to the UES of air purification supplied by various urban ecosystems, it is found that the demand for air purification UES is greater than that of the supply, especially in the urban fabric (111, 112) and industrial unit (121). Therefore, the comparison would help policy makers identify the need or priority of GI implementation in urban areas (Derkzen et al., 2015; McDonald, 2009; Ramyar et al., 2020).

Provisioning UES capacity & supply

For the state condition of urban vegetation coverage, it is a general indicator of the UES capacity of different urban ecosystems since many studies have shown that the importance of green spaces in providing various ecosystem services (Andersson et al., 2014; Cameron et al., 2012; Dallimer et al., 2012; Holt et al., 2015; Tzoulas et al., 2007). The larger the vegetation coverage, the greater the UES capacity is and so is the UES supply, especially for the provisioning UES. Nonetheless, vegetation cover is still only a board indicator. The composition of different vegetation in urban areas is another important factor to be considered during GI planning.

Cultural UES capacity & supply

For another state condition of land use expressing in terms of the proportion of urban green space, it shows a different relationship with UES comparing to the urban vegetation coverage. The conditions of urban green space and urban vegetation coverage for most urban ecosystems are similar except for those discrepancies caused by the privacy of the lands for agriculture and pasture. The recreation UES supply does not show a direct relationship with the coverage of urban green space. It may imply that the quality of the urban green space would be another subjective factor, accompanying the size of area, in determining the recreation UES supply. Among most UES, cultural UES is more subjective than the others because it is usually affected by social factors of different people's throughs and preferences which cannot be quantified and concluded easily.

4.2 Comparison to other studies

UES distribution & trade-off among UGS components

Under the same UES quantification method, this study in Cheltenham shows an obvious trend of increase in UES supply from the town centre to peripheral while that in Rotterdam by Derkzen et al. (2015) shows a more random pattern across the city. It would be explained by the differences in the UGS coverage pattern due to various geographical and urban contexts.

UGS coverage in Cheltenham is dominated by herbaceous vegetation and private gardens while Rotterdam mainly consists of not only herbaceous vegetations and private garden but also more water surfaces of the canal system penetrating the entire city. Nevertheless, both results show mostly synergies among the UGS components so as the 6 UES since UGS components can provide multiple UES despite their various capacities (Derkzen et al., 2015).

Other multiple-UES studies in the UK

Although there are some multiple UES studies in the UK over the past 20 years (Holt et al., 2015; Radford and James, 2013; Tratalos et al., 2007; Whitford et al., 2001), it is difficult to compare the results among studies because of the differences in the scales of the studies, types of UES selected and quantification methods of UES. Nonetheless, most studies show that land cover types are basic and important elements in quantifying UES. Therefore, the use of UGS components and UES supply rates in our study help simplify and standardise the UES quantification as well as facilitate comparisons during local GI planning.

On the other hand, there are also current projects of mapping natural capital and ES based on existing habitats in England carried out by Centre for Ecology and Hydrology (CEH), Natural England (CEH, 2020; Natural England, 2014). However, the use of CEH Landcover Map is more suitable in assessing ES in a regional scale instead of local scale as maps with limiting resolution (1km2 to 25m2 pixels) are not reliable for local studies unless additional data or fine-adjustments are provided (Dales et al, 2014).

4.3 GI strategies in Cheltenham

The current GI strategies in Cheltenham are more focusing on the enhancement of existing GI connectivity and relieving the problem of flooding with River Chelt (JCS Local Planning Authorities, 2014). They are planned to strengthen the connectivity of GI, especially among the urban open spaces and surrounding countryside, by improvements of attractiveness to people and wildlife in the form of green corridors, such as Honeybourne railway line, old Kingham line and river courses (JCS Local Planning Authorities, 2014). For the flooding issue, it mainly focuses on the River Chelt culvert under the town centre and pinch points of water course built over or truncated by traffic roads (JCS Local Planning Authorities, 2014).

Connectivity of GI falls on the cultural UES category while flooding relief is one of the regulating UES. Unfortunately, both UES are not directly addressed in this study due to the lack of data. Nevertheless, our result of the pattern of recreation UES supply increasing across Cheltenham urban core to surrounding rural area supports the GI connectivity strategies planned. On the other hand, the result of run-off retention UES also provides evidence that improvement of impervious surface should be carried out in the urban core in order to reduce the peak runoff into the river courses and the chance of flooding. The mapped information of current UGS components could provide further spatial distribution and UES supply potential for detail planning and design for the enhancement.

4.4 MAES & UGS components in GI Planning

Other than supporting the current GI strategies, our MAES result would also help in the formulation of new GI implementation strategies. In MAES framework, current UEC and UES would be assessed and mapped in accordance with the urban ecosystem types. The relationships discovered among UEC and UES (Section 4.1) would be utilised in the GI strategies planning using UGS components as the basic units, which are also the basic elements used in UES quantification in this study.

According to the result form MAES, it provides background information of UEC and UES for an urban area to the policy makers to determine the main purposes of the GI strategic planning.

Cheltenham as example, in the aspect of PM_{10} concentration, the demand for air purification UES is greater than that of the supply in most areas. Therefore, the council should enhance the supply of corresponding UES by introducing new GI.

In order to facilitate simple quantification and estimation of UES in the design and planning stage, UGS components consisting of various vegetation are suggested to be the basic elements used to comprise the urban GI.

In regard to different UEC, the UES needed to be enhanced for various urban ecosystem sub- areas would be figured out easily. Therefore, policy makers would prioritise the specific needs for each area. In Cheltenham, the PM_{10} concentration pressure on the urban fabric (111, 112) and industrial site (121) is the most serious while the current air purification UES supply there is not enough to relieve the pressure. So, more UGS units should be planned in these 2 sites in priority.

Having the basic elements and proximate locations, the next step would be how these elements are being put together in terms of composition, spatial pattern and quality according to the local contexts, i.e. site-specific opportunities and constraints. Different combinations would also be tested to result the best synergy effect of various UES. In the continuous urban fabric sub-area, i.e. the town centre, additional screening vegetation would be added to road side since road traffic is one of the main sources of PM_{10} in Cheltenham. The vegetation should consist of more shrubs because of its higher UES capacity rate in air purification. Planting in long and strip patterns along the road would not only be effective in capturing PM_{10} but also screen the noise from traffic. In the continuous urban fabric sub-area, i.e. the town centre, additional screening vegetation would be added to road side since road traffic is one of the main sources of PM_{10} in Cheltenham. The vegetation should consist of more shrubs because of its higher UES capacity rate in air purification. Planting in long and strip patterns along the road would not only be effective in capturing PM_{10} but also screen the noise from traffic.

Nevertheless, it is a simple and preliminary approach for policy makers to combine the MAES result with the use of UGS components in urban GI planning while the UES enhancement would be estimated generally in the early stage of urban planning. Economic and social factors should also be considered in the long-term and detailed GI planning (Benedict et al., 2006; Mell et al., 2016; Vandermeulen et al., 2011).

The knowledge would also be used in establishment of local urban design or planning guidelines in the long run. For example, the urban design guidelines for roadside or street as well as the private garden in different types of housing development (CEDD, 2020; Department of Environment, Land, Water and Planning, 2017; San Francisco Planning

Department, 2018; Tratalos et al., 2007) would help the enhancement of UES.

4.5 Limitations

UGS component data source

In this study, although most primary data are easily accessed, there is still the lack of formal inventory for tree or shrub information of Cheltenham, which is a typical small town comparing to those larger cities such as London or Birmingham.

Also, due to the limited availability of multi-spectral satellite imagery and up-to-date Lidar data for further vegetation type identification by computer processing (Ardila et al., 2012; Ellis and Mathews, 2019; Momeni et al., 2016; Moskal et al., 2011), such as the use of multispectral threshold segmentation or normalised digital surface model (nDSM), only visual interpretation and manual mapping of trees and shrubs are adopted in this study.

Despite the high accuracy, the method is relatively time-consuming and tedious for larger cities.

UES quantification method

UES in this study is calculated as the sum of product of the coverages of individual UGS and corresponding UES supply rates within different urban ecosystem sub-areas. The UES supply rates resulted are based on the literature review method from Derkzen et al. (2015) with corresponding adjustments specific to the UK situation.

However, it may cause an imbalance in some literature data. UES supply rate of carbon storage as an example, the data mainly referenced from 2 literatures of the UK studies; while for that of air purification, since there is lacking former research for some UGS units in the UK, more literature data from other countries' studies are used. Nonetheless, countries with similar characteristics with the UK are chosen in priority.

5 Conclusion

In this study, it shows the contribution of using UGS as the basic components in GI strategy planning for urban EC and ES.

1. Using UGS as the basic units during planning process, policy makers can stimulate different GI strategy by changing the composition (coverage and type) and spatial arrangement of UGS (Andersson et al., 2014; Derkzen et al., 2015). Synergy or trade-off of UES due to various UGS planning would be estimated more easily for policy decision making.
2. Integrating the UEC and UES results help avoid the potential mismatches between supply and demand of UES by identifying which UES is in priority in the target area (Andersson et al., 2015; Faehnle et al., 2015; Pulighe et al., 2016). The assessment and mapping of UEC gives some insights for the demand side of UES of which only few studies are found (Grêt-Regamey et al., 2012; Haase et al. 2014; McPhearson et al., 2013). It gives evidence and support to the new GI implementation approach based on UGS components respective to their specific UES capacities and spatial characteristics.
3. The small scale of UGS components allows detail planning in local urban GI strategy. Using the same basic units, it also fosters the comparison as well as the formation of GI networks among different towns and cities.
4. The UGS component coverage and UES supply rate from literature data as well as high-resolution data are easily available to policy makers for evaluating UEC and UES. A set of simple supply rates for specific UES by different UGS components is summarised and incorporated in other future studies.

Furthermore, future research should assess provisioning UES such as the food production by urban edible green UGS, such as roof garden (Russo and Cirella, 2019; Russo et al., 2017). Urban ecosystem disservices should also be taken into consideration in the trade-off with UES supply by various UGS (Lyytimäki and Sipilä, 2009; Speak et al., 2018). Last but not least, engagement and participation of local stakeholders are absolutely essential elements in building strong visions and aims for local GI strategies and planning (Pulighe et al., 2016; Luederitz et al. 2015; Nahuelhual et al. 2015).

References

Aertsens, J., De Nocker, L., Lauwers, H., Norga, K., Simoens, I., Meiresonne, L., Turkelboom, F. and Broekx, S. (2012) Daarom Groen! Waarom U Wint Bij Groen in Uw Stad of Gemeente. VITO, Mol.

Andersson, E., Barthel., S., Borgström, S., Colding, J., Elmqvist, T., Folke, C. and Gren, A. (2014) 'Reconnecting cities to the biosphere: stewardship of green infrastructure and urban ecosystem services', AMBIO, 43, pp. 445–453. doi 10.1007/s13280-014-0506-y.

Andersson, E., McPhearson, T., Kremer, P., Gomez-Baggethun, E., Haase, D., Tuvendal, M. and Wurster, D. (2015) 'Scale and context dependence of ecosystem service providing units', Ecosystem Services, 12, pp. 157–164. doi 10.1016/j.ecoser. 2014.08.001.

Ardila, J.P., Bijker, W., Tolpekin, V.A. and Stein, A. (2012) 'Context-sensitive extraction of tree crown objects in urban areas using VHR satellite images', International Journal of Applied Earth Observation and Geoinformation, 15, pp. 57-69. doi 10.1016/j. jag.2011.06.005.

Belmeziti, A., Cherqui, F., & Kaufmann, B. (2018). Improving the multi-functionality of urban green spaces: Relations between components of green spaces and urban services. Sustainable Cities and Society, 43(April), 1–10. https://doi.org/10.1016/j.scs. 2018.07.014

Armson, D., Stringer, P. and Ennos, a. R. (2012) 'The effect of tree shade and grass on surface and globe temperatures in an urban area', Urban Forestry & Urban Greening, 11, pp. 245–255. doi 10.1016/j.ufug.2012.05.002.

Baumgardner, D., Varela, S., Escobedo, F.J., Chacalo, A. and Ochoa, C. (2012) 'The role of a peri-urban forest on air quality improvement in the Mexico City megalopolis', Environmental Pollution, 163, pp. 174-183. doi 10.1016/j.envpol.2011.12.016.

Benedict, M.A. and McMahon, E.T. (2006) Green infrastructure: linking landscapes and communities. Washington, DC: Island Press.

Bolund, P. and Hunhammar, S. (1999) 'Ecosystem services in urban areas', Ecological Economics, 29, pp. 293–301. doi 10.1016/ S0921-8009(99)00013-0.

Burkhard, B., Fernando, S., Nedkov, S. and Maes, J. (2018) 'An operational framework for integrated Mapping and Assessment of Ecosystems and their Services (MAES)', One Ecosystem, 3: e22831. doi 10.3897/oneeco.3.e22831.

Burkhard, B., Kroll, F., Nedkov, S. and Müller, F. (2012) 'Mapping ecosystem service supply, demand and budgets', Ecological Indicators, 21, pp. 17-29. doi 10.1016/j.ecolind.2011.06.019.

Burkhard, B., Kroll, F. and Windhorst, W. (2009) 'Landscapes' Capacities to Provide Ecosystem Services – a Concept for Land-Cover Based Assessments', Landscape Online, 15, pp. 1-22. doi 10.3097/LO.200915.

Burkhard, B. and Maes, J. (2017) 'Chapter 1. Introduction', in Burkhard, B. and Maes, J. (eds.) Mapping Ecosystem Services. 1st edn. Bulgaria: Pensoft Publishers, Sofia. Pp. 23-25. doi 10.3897/ab.e12837.

Cameron, R.W.F., Blanuša, T., Taylor, J.E., Salisbury, A., Halstead, A.J., Henricot, B. and Thompson, K. (2012) 'The domestic garden – its contribution to urban green infrastructure', Urban Forestry & Urban Greening, 11, pp. 129–137. doi 10.1016/j. ufug.2012.01.002.

Cavanagh, J.A.E., Zawar-Reza, P. and Gaines Wilson, J. (2009) 'Spatial attenuation of ambient particulate matter air pollution within an urbanised forest patch', Urban Forestry & Urban Greening, 8, pp. 21–30. doi 10.1016/j.ufug.2008.10.002.

CEDD, Civil Engineering and Development Department (2020). Kai Tak Development Urban Design Guidelines and Manual. Available at: https://www.ktd.gov.hk/udgm/en/? (Accessed 15 May 2020).

CEH, Centre for Ecology & Hydrology (2020) Natural England natural capital maps. Available at: https://eip.ceh.ac.uk/ naturalengland-ncmaps (Accessed 24 Jul. 2020).

Chang, J., Qu, Z., Xu, R., Pan, K., Xu, B., Min, Y., … Ge, Y. (2017). Assessing the ecosystem services provided by urban green spaces along urban center-edge gradients. Scientific Reports, 7(1), 11226. https://doi.org/10.1038/s41598-017-11559-5

Cheltenham Borough Council (2006). Cheltenham Borough Local Plan Second Review. Available at: https://www. cheltenham.gov.uk/info/46/planning_policy/171/local_plan_second_review_200 6 (Accessed 21 Jan. 2020).

Cheltenham Borough Council (2020). Introduction to historic Cheltenham. Available at: https://www.cheltenham.gov.uk/info/37/ local_history_and_heritage/272/historic_cheltenham (Accessed 15 May 2020).

Copernicus (2020a) 'Corine Land Cover 2018 - ESRI FGDB' [FileGeoDatabase geospatial data], version 2020_20u1. Available at: https://land.copernicus.eu/pan-european/corine-land- cover/clc2018?tab=download (Accessed 4 Apr. 2020).

Copernicus (2020b) Copernicus Sentinel 2 colour infrared (Bands 843) [TIFF geospatial data], Tiles: so, 1: 20000. Available at: https://digimap.edina.ac.uk/pilot (Accessed 4 Apr. 2020).

Dales, N.P., Brown, N.J. and Lusardi, J. (2014). 'Assessing the potential for mapping ecosystem services in England based on existing habitats', Natural England Research Reports, Number 056. Available at: file:///C:/Users/onyil/Downloads/NERR056 _edition_1.pdf (Accessed 24 Jul. 2020).

Dallimer, M., Irvine, K., Skinner, A.M.J., Davies, Z.G., Rouquette, J.R., Maltby, L.L., Warren, P.H., Armsworth, P.R. and Gaston, K.J. (2012) 'Biodiversity and the feel-good factor: understanding associations between self-reported human well-being and species richness', BioScience, 62, pp. 47–55. doi 10.1525/bio.2012.62.1.9.

Davies, Z.G., Edmondson, J.L., Heinemeyer, A., Leake, J.R. and Gaston, K.J. (2011) 'Mapping an urban ecosystem service: quantifying above-ground carbon storage at a city- wide scale', Journal of Applied Ecology, 48, pp. 1125–1134. doi 10.1111/ j.1365- 2664.2011.02021.x.

Department of Environment, Land, Water and Planning (2017). Urban Design Guidelines for Victoria. Available at: https://www.urban-design-guidelines.planning.vic.gov.au/?_ga=2.84643665.99679902.1594238718-1244921233.159423871 8 (Accessed 15 May 2020).

Derkzen, M.L., Teeffelen, A.J.A. and Verburg, P.K. (2015) 'Quantifying urban ecosystem services based on high resolution data of urban green space: an assessment for Rotterdam, the Netherlands', Journal of Applied Ecology, 52, pp. 1020-1032. doi 10.1111/1365-2664.12469.

EEA, European Environmental Agency (2020). The Common International Classification of Ecosystem Services Version 5.1.

Available at: https://cices.eu/ (Accessed 15 May 2020).
Ellis, E.A. and Mathews, A. J. (2019) 'Object-based delineation of urban tree canopy: assessing change in Oklahoma City, 2006–2013', Computers, Environment and Urban Systems, 73, pp. 85-94. doi 10.1016/j.compenvurbsys.2018.08.006.
Escobedo, F.J. and Nowak, D.J. (2009) 'Spatial heterogeneity and air pollution removal by an urban forest', Landscape and Urban Planning, 90, pp. 102-110. doi 10.1016/j.landurbplan.2008.10.021.
European Commission (2019). Maintain and restore ecosystems – Target 2. Available at: https://ec.europa.eu/environment/nature/biodiversity/strategy/target2/index_en.htm (Accessed 21 Jan. 2020).
Faehnle, M., Söderman, T., Schulman, H. and Lehvävirta, S. (2015) 'Scale-sensitive integration of ecosystem services in urban planning', GeoJournal, 80, pp. 411–425. doi 10.1007/s10708-014-9560-z.
Fang, C.F. and Ling, D.L. (2003) 'Investigation of the noise reduction provided by tree belts', Landscape and Urban Planning, 63, pp. 187-195. doi 10.1016/S0169-2046(02)00190-1.
Fowler, D., Skiba, U., Nemitz, E., Choubedar, F., Branford, D., Donovan, R. and Rowland, P. (2004) 'Measuring aerosol and heavy metal deposition on urban woodland and grass using inventories of 210Pb and metal concentrations in soil', Water, Air and Soil Pollution Focus, 4, pp. 483–499. doi 10.1023/B:WAFO.0000028373.02470.ba.
Getmapping (2018) High Resolution (25cm) Vertical Aerial Imagery [JPG geospatial data], Tiles: so9017,so9018,so9019, so9020,so9021,so9022,so9023,so9024,so9025,so9026,so9117,so9118,so9119,so9120,so9121,so9122,so9123,so9124,so9125, so9126,so9217,so9218,so9219,so9220,so9221,so9222,so9223,so9224,so9225,so9226,so9317,so9318,so9319,so9320,so9321, so9322,so9323,so9324,so9325,so9326,so9417,so9418,so9419,so9420,so9421,so9422,so9423,so9424,so9425,so9426,so9517, so9518,so9519,so9520,so9521,so9522,so9523,so9524,so9525,so9526,so9617,so9618,so9619,so9620,so9621,so9622,so9623, so9624,so9625,so9626,so9717,so9718,so9719,so9720,so9721,so9722,so9723,so9724,so9725,so9726,so9817,so9818,so9819, so9820,so9821,so9822,so9823,so9824,so9825,so9826,so9917,so9918,so9919,so9920,so9921,so9922,so9923,so9924,so9925, so9926, 1:500. Available at: https://digimap.edina.ac.uk/aerial (Accessed 4 Apr. 2020).
Gren, Å., & Andersson, E. (2018). Being efficient and green by rethinking the urban-rural divide—Combining urban expansion and food production by integrating an ecosystem service perspective into urban planning. Sustainable Cities and Society, 40, 75–82. https://doi.org/10.1016/j.scs.2018.02.031
Grêt-Regamey, A., Weibel, B., Kienast, F., Rabe, S.-E. and Zulian, G. (2015) 'A tiered approach for mapping ecosystem services', Ecosystem Services, 13, pp. 16–27. doi.10.1016/j.ecoser.2014.10.008.
Haase, D., Larondelle, N., Andersson, E., Artmann, M., Borgström, S., Breuste, J., Gomez- Baggethun, E., Gren, Å., Hamstead, Z., Hansen, R., Kabisch, N., Kremer, P., Langemeyer, J., Rall, E.L., McPhearson, T., Pauleit, S., Qureshi, S., Schwarz, N., Voigt, A., Wurster, D. and Elmqvist, T. (2014) 'A quantitative review of urban ecosystem service assessments: Concepts, models, and implementation', AMBIO, 43, pp. 413–433. doi. 10.1007/s13280-014- 0504-0.
Haines-Young, R. and Potschin, M. (2013) CICES V4.3 - Report prepared following consultation on CICES Version 4. EEA Framework Contract No EEA/IEA/09/003 Available at: https://unstats.un.org/unsd/envaccounting/seeaRev/GCComments/CICES_Report.pdf (Accessed 21 Jan. 2020).
Holt, A.R., Mears, M., Maltby, L. and Warren, P. (2015) 'Understanding spatial patterns in the production of multiple urban ecosystem services', Ecosystem Services, 16, pp. 33-46. doi 10.1016/j.ecoser.2015.08.007.
Huete, A.R. and Liu, H. (1994) 'An error and sensitivity analysis of the atmospheric- and soil-correcting variants of the NDVI for the MODIS-EOS', IEEE Transactions on Geoscience and Remote Sensing, 32, pp. 897-905. doi 10.1109/36.298018.
IPCC (2018) Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press. Available at: https://www.ipcc.ch/sr15/ (Accessed 28 Dec. 2020).
IPCC (2019) Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press. Available at: https://www.ipcc.ch/srccl/ (Accessed 28 Dec. 2020).
JCS Local Planning Authorities (2014) Joint Core Strategy - Green infrastructure Strategy. Available at: https://www.jointcorestrategy.org/examination (Accessed 21 Jan. 2020).
JCS Local Planning Authorities (2017) Gloucester, Cheltenham and Tewkesbury - Joint Core Strategy2011 - 2031. Available at: https://www.jointcorestrategy.org/ (Accessed 21 Jan. 2020).
Jiang, Z., Huete, A.R., Chen, J., Chen, Y., Li, J., Yan, G. and Zhan, X. (2006) 'Analysis of NDVI and scaled difference vegetation index retrievals of vegetation fraction', Cities, 92, pp. 59-70. doi 10.1016/j.rse.2006.01.003.
Kourdounouli, C., & Jönsson, A. M. (2020) Urban ecosystem conditions and ecosystem services – a comparison between large urban zones and city cores in the EU. Journal of Environmental Planning and Management, 63(5), 798–817. https://doi.org/10.1080/09640568.2019.1613966
Leprieur, C., Kerr, Y.H., Mastorchio, S., and Meunier, J.C. (2000) 'Monitoring vegetation cover across semi-arid regions: Comparison of remote observations from various scales', International Journal of Remote Sensing, 21, pp. 281-300. doi 10.1080/014311600210830.
Luederitz, C., Brink, E., Gralla, F., Hermelingermeier, V., Meyer, M., Niven, L., Panzer, L., Partelow, S., Rau, A.-L., Sasaki, R.,

Abson, D.J., Lang, D.J., Wamsler, C. and von Wehrden, H. (2015) 'A review of urban ecosystem services: six key challenges for future research', Ecosystem Services, 14, pp. 98–112. doi 10.1016/S0921-8009(99)00013-0.

Lyytimäki, J. and Sipilä, M. (2009) 'Hopping on one leg – The challenge of ecosystem disservices for urban green management', Urban Forestry & Urban Greening, 8(4), pp. 309- 315. doi 10.1016/j.ufug.2009.09.003.

Maes, J., Liquete, C., Teller, A., Erhard, M., Paracchini, M.L. , Barredo, J., Grizzetti, B., Cardoso, A., Somma, F., Petersen, J., Meiner, A., Gelabert, E.R., Zal, N., Kristensen, P., Bastrup-Birk, A., Biala, K., Piroddi, C., Egoh, B., Degeorges, P., Fiorina, C., Santos-Martín, F., Naruševičius, V., Verboven, J., Pereira, H., Bengtsson, J., Gocheva, K., Marta-Pedroso, C., Snäll, T., Estreguil, C., San-Miguel-Ayanz, J., Pérez-Soba, M., Grêt-Regamey, A., Lillebø, A., Malak, D.A., Condé, S., Moen, J., Czúcz, B., Drakou, E., Zulian, G. & Lavalle, C. (2016a) 'An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020', Ecosystem Services, 17, pp. 14 23. doi 10.1016/j.ecoser.2015.10.023.

Maes, J., Teller, A., Erhard, M., Grizzetti, B., Barredo, J.I., Paracchini, M.L., Condé, S., Somma, F., Orgiazzi, A., Jones, A., Zulian, A., Vallecilo, S., Petersen, J.E., Marquardt, D., Kovacevic, V., Abdul Malak, D., Marin, A.I., Czúcz, B., Mauri, A., Loffler, P., BastrupBirk, A., Biala, K., Christiansen, T. and Werner, B. (2018) Mapping and Assessment of Ecosystems and their Services: An analytical framework for ecosystem condition. Publications office of the European Union, Luxembourg. Available at: https://catalogue.biodiversity.europa.eu/uploads/document/file/1673/5th_MAES_report.pdf (Accessed 13 Mar. 2020).

Maes, J., Zulian, G., Thijssen, M., Castell, C., Baró, F., Ferreira, A.M., Melo, J., Garrett, C.P., David, N., Alzetta, C., Geneletti, D.; Cortinovis, C., Zwierzchowska, I., Louro Alves, F., Souto Cruz, C., Blasi, C., Alós Ortí, M.M., Attorre, F., Azzella, M.M., Capotorti, G., Copiz, R., Fusaro, L., Manes, F., Marando, F., Marchetti, M., Mollo, B., Salvatori, E., Zavattero, L., Zingari, P.C., Giarratano, M.C., Bianchi, E., Duprè, E., Barton, D., Stange, E., Perez-Soba, M., van Eupen, M., Verweij, P., de Vries, A., Kruse, H., Polce, C., Cugny- Seguin, M., Erhard, M., Nicolau, R., Fonseca, A., Fritz, M. and Teller, A. (2016b) Mapping and Assessment of Ecosystems and their Services. Urban Ecosystems. Publications Office of the European Union, Luxembourg. Available at: https://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/pdf/102.pdf (Accessed 13 Mar. 2020).

McDonald, A.G., Bealey, W.J., Fowler, D., Dragosits, U., Skiba, U., Smith, R.I., Donovan, R.G., Brett, H.E., Hewitt, C.N. and Nemitz, E. (2007) 'Quantifying the effect of urban tree planting on concentrations and depositions of PM_{10} in two UK conurbations', Atmospheric Environment, 41, pp. 8455-8467. doi 10.1016/j.atmosenv.2007.07.025.

McDonald, R.I. (2009) 'Ecosystem service demand and supply along the urban-to-rural gradient', Journal of Conservation Planning, 5, pp. 1–14. doi 10.13140/RG.2.1.3677.8088.

McPhearson, T., Kremer, P. and Hamstead, Z.A. (2013) 'Mapping ecosystem services in New York City: applying a social–ecological approach in urban vacant land', Ecosystem Services, 5, pp. 11–26. doi 10.1016/j.ecoser.2013.06.005.

McPherson, E.G., Simpson, J.R., Xiao, Q. and Wu, C. (2011) 'Million trees Los Angeles canopy cover and benefit assessment', Landscape and Urban Planning, 99, pp. 40–50. doi 10.1016/j.landurbplan.2010.08.011.

Mell, I.C., Henneberry, J., Hehl-Lange, S. and Keskin, B. (2016) 'To green or not to green: Establishing the economic value of green infrastructure investments in The Wicker, Sheffield', Urban Forestry & Urban Greening, 18, pp. 257-267. doi 10.1016/j.ufug.2016.06.015.

Met Office (2016) South West England: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/ metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/south-west-england_-climate---met-office.pdf (Accessed 15 May 2020).

Momeni, R., Aplin, P. and Boyd, D.S. (2016) 'Mapping Complex Urban Land Cover from Spaceborne Imagery: The Influence of Spatial Resolution, Spectral Band Set and Classification Approach', Remote Sensing, 8(2), pp. 88. doi 10.3390/rs8020088.

Moskal, L.M., Styers, D.M. and Halabisky, M. (2011) 'Monitoring Urban Tree Cover Using Object-Based Image Analysis and Public Domain Remotely Sensed Data', Remote Sensing, 3, pp. 2243-2262. doi 10.3390/rs3102243.

NAEI, National Atmospheric Emission Inventory 2017 (2019) UK Emissions Interactive Map [CSV data]. Available at: https://naei.beis.gov.uk/emissionsapp/ (Accessed 21 Jan. 2020).

Nahuelhual, L., Laterra, P., Villarino, S., Mastrángelo, M., Carmona, A., Jaramillo, A., Barral, P. and Burgos, N. (2015) 'Mapping of ecosystem services: missing links between purposes and procedures', Ecosystem Services, 13, pp. 162–172. doi 10.1016/j.ecoser.2015.03.005.

Natural England (2014) Assessing the potential for mapping ecosystem services in England based on existing habitats (NERR056). Available at: http://publications.naturalengland.org.uk/publication/5280919459987456?category=38019 (Accessed 24 Jul. 2020).

Nedkov, S., Zhiyanski, M., Nikolova, M., Gikov, A., Nikolov, P. and Todorov, L. (2016) 'Mapping of carbon storage in urban ecosystems: a Case study of Pleven District, Bulgaria', Scientific conference Geographical aspects of land use and planning under climate change. Available at: https://www.researchgate.net/publication/309319661_Mapping_of_carbon_storage_in _urban_ecosystems_a_Case_study_of_Pleven_District_Bulgaria (Accessed 21 Jan. 2020).

Office for National Statistics (2019) Overview of the UK population: August 2019. Available at: https://www.ons.gov.uk/people populationandcommunity/populationandmigration/populationestimates/articles/overviewoftheukpopulation/august2019#statisticians-comment (Accessed 15 May 2020).

Ordnance Survey GB (2019a) Boundary-Line™ [SHAPE geospatial data], Tiles: GB, 1: 10000. Available at: https://digimap.edina.ac.uk/os (Accessed 4 Apr. 2020).

Ordnance Survey GB (2019b) OS MasterMap Greenspace [SHAPE geospatial data], Tiles: so91nw,so92sw,so92nw,so91ne,so92se, so92ne, 1:2500. Available at: https://digimap.edina.ac.uk/os (Accessed 4 Apr. 2020).

Ordnance Survey GB (2019c) OS Open Map - Local [SHAPE geospatial data], Tiles: so, 1: 10000. Available at: https://digimap.edina.ac.uk/os (Accessed 4 Apr. 2020).

Ostle, N.J., Levy, P.E., Evans, C.D. and Smith, P. (2009) 'UK land use and soil carbon sequestration', Land Use Policy, 26S, pp. S274-S283. doi 10.1016/j.landusepol.2009.08.006.

Pandit, A. and Gopalakrishnan, G. (1996) 'Estimation of Annual Storm Runoff Coefficients by Continuous Simulation', Journal of Irrigation and Drainage Engineering, 122, pp.211– 220. doi 10.1061/(ASCE)0733-9437(1996)122:4(211).

Peng, W., Kuang, T. and Tao, S. (2019) 'Quantifying influences of natural factors on vegetation NDVI changes based on geographical detector in Sichuan, western China', Journal of Cleaner Production, 233, pp. 353-367. doi 10.1016/j.jclepro.2019.05.355.

Pulighe, G., Fava, F. and Lupia, F. (2016) 'Insights and opportunities from mapping ecosystem services of urban green spaces and potentials in planning', Ecosystem Services, 22, pp. 1-10. doi 10.1016/j.ecoser.2016.09.004.

Radford, K.G. and James, P. (2013) 'Changes in the value of ecosystem services along a rural-urban gradient: A case study of Greater Manchester, UK'. Landscape and Urban Planning, 109(1), pp. 117–127. doi 10.1016/j.landurbplan.2012.10.007.

Ramyar, R., Saeedi, S., Bryant, M., Davatgar, A. and Hedjri, G.M. (2020) 'Ecosystem services mapping for green infrastructure planning–The case of Tehran', Science of the Total Environment, 703, pp. 135466. doi 10.1016/j.scitotenv.2019.135466.

Ramyar, R. and Zarghami, E. (2017) 'Green infrastructure contribution for climate change adaptation in urban landscape context', Applied Ecology and Environmental Research, 15(3), pp. 1193–1209. doi 10.15666/aeer/1503_11931209.

Revi, A., D.E. Satterthwaite, F. Aragón-Durand, J., Corfee-Morlot, R.B.R., Kiunsi, M., Pelling, D.C., Roberts, W. & Solecki, (2014) Urban areas. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535-612. Available at: https://www.ipcc.ch/report/ar5/wg2/ (Accessed 13 Mar. 2020).

Ronchi, S., Arcidiacono, A., & Pogliani, L. (2020). Integrating green infrastructure into spatial planning regulations to improve the performance of urban ecosystems. Insights from an Italian case study. Sustainable Cities and Society, 53, 101907. https://doi.org/10.1016/j.scs.2019.101907

Roussel, F., Schulp, C.J.E., Verburg, P.H. and Teeffelen, A.J.A. (2017) 'Testing the applicability of ecosystem services mapping methods for peri-urban contexts: A case study for Paris', Ecological Indicators, 83, pp. 504-514. doi 10.1016/j.ecolind.2017.07.046.

Russo, A., Escobedo, F. J. and Zerbe, S. (2016) 'Quantifying the local-scale ecosystem services provided by urban treed streetscapes in Bolzano, Italy', AIMS Environmental Science, 3(1), pp. 58–76. doi: 10.3934/environsci.2016.1.58.

Russo, A. and Cirella, G.T. (2019) 'Edible urbanism 5.0', Palgrave Communications, 5(1), pp. 163. doi 10.1057/s41599-019-0377-8.

Russo, A., Escobedo, F.J., Cirella, G.T. and Zerbe, S. (2017) 'Edible green infrastructure: An approach and review of provisioning ecosystem services and disservices in urban environments', Agriculture, Ecosystems & Environment, 242, pp. 53–66. doi 10.1016/j.agee.2017.03.026.

Samara, T. and Tsitsoni, T. (2011) 'The effects of vegetation on reducing traffic noise from a city ring road', Noise Control Engineering Journal, 59(1), pp. 68-74. doi 10.3397/1.3528970.

San Francisco Planning Department (2018). San Francisco Urban Design Guidelines. Available at: https://sfplanning.org/resource/urban-design-guidelines (Accessed 15 May 2020).

Sentinel-Hub (2020) Normalized difference vegetation index. Available at: https://custom-scripts.sentinel-hub.com/custom-scripts/sentinel-2/ndvi/ (Accessed 15 May 2020).

Skelhorn, C., Lindley, S. and Levermore, G. (2014) 'The impact of vegetation types on air and surface temperatures in a temperate city: A fine scale assessment in Manchester, UK', Landscape and Urban Planning, 121, pp. 129–140. doi 10.1016/j.landurbplan.2013.09.012.

Soil Conservation Service (1972) SCS National Engineering Handbook, United States Department of Agriculture. Washington, DC.

Speak, A., Escobedo, F.J., Russo, A. and Zerbe, F. (2018) 'An ecosystem service-disservice ratio: Using composite indicators to assess the net benefits of urban trees', Ecological Indicators, 95, pp. 544-553. doi 10.1016/j.ecolind.2018.07.048.

Smith, R.M., Gaston, K.J., Warren, P.H. and Thompson, K. (2005) 'Urban domestic gardens (V): relationships between landcover composition, housing and landscape', Landscape Ecology, 20, pp. 235–253. doi 10.1007/s10980-004-3160-0.

Tallis, M., Taylor, G., Sinnett, D. and Freer-Smith, P. (2011) 'Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments', Landscape and Urban Planning, 103, pp. 129-138. doi 10.1016/j.landurbplan.2011.07.003.

Tratalos, J., Fuller, R.A., Warren, P.H., Davies, R.G. and Gaston, K.J. (2007) 'Urban form, biodiversity potential and ecosystem services', Landscape and Urban Planning, 83, pp. 308– 317. doi 10.1016/j.landurbplan.2007.05.003.

Tzoulas, K., Korpela, K., Venn, S., Yli-Pelkonen, V., Kaźmierczak, A., Niemela, J. and James, P. (2007) 'Promoting ecosystem and human health in urban areas using green infrastructure: a literature review', Landscape and Urban Planning, 81, pp. 167–178. doi 10.1016/j.landurbplan.2007.02.001.

United Nation (2018) The World's Cities in 2018. Available at: https://population.un.org/wup/Publications/ (Accessed 13 Mar. 2020).

USDA, United States Department of Agriculture (1986) Urban Hydrology for Small Watersheds. Available at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf (Accessed 15 May 2020).

Van Renterghem, T., Botteldooren, D. and Verheyen, K. (2012) ‘Road traffic noise shielding by vegetation belts of limited depth’, Journal of Sound and Vibration, 331, pp. 2404–2425. doi 10.1016/j.jsv.2012.01.006.
Vandermeulen, V., Verspecht, A., Vermeire, B., Huylenbroeck, G.V. and Gellynck, X. (2011) ‘The use of economic valuation to create public support for green infrastructure investments in urban areas’, Landscape and Urban Planning, 103(2), pp. 198-206. doi 10.1016/j.landurbplan.2011.07.010.
Vos, P.E.J., Maiheu, B., Vankerkom, J. and Janssen, S. (2013) ‘Improving local air quality in cities: to tree or not to tree?’, Environmental Pollution, 183, pp. 113–22. doi 10.1016/j.envpol.2012.10.
Weber, T., Sloan, A. and Wolf, J. (2006) ‘Maryland's green infrastructure assessment: development of a comprehensive approach to land conservation’, Landscape and Urban Planning, 77(1-2), pp. 94–110. doi 10.1016/j.landurbplan.2005.02.002.
Whitford, V., Ennos, A.R. and Handley, J.F. (2001) ‘City form and natural process-indicators for the ecological performance of urban areas and their application to Merseyside, UK’, Landscape and Urban Planning, 57(2), pp. 91–103. doi 10.1016/S0169-2046(01)00192-X.
Zhang, S. and Ramírez, F.M. (2019) ‘Assessing and mapping ecosystem services to support urban green infrastructure: The case of Barcelona, Spain’, Remote Sensing of Environment. 101, pp. 366-378. doi 10.1016/j.cities.2019.03.016.

Table 1 UES classes & indicators

CICES Section	CICES Class Type	Indicator (unit)
Regulating and maintenance ecosystem service	Regulation of air quality by urban vegetation	Air PM_{10} purification ($g/m^2/year$)
	Climate regulation by reduction of CO_2	Carbon storage (kg/m^2)
	Noise mitigated by urban vegetation	Noise reduction (dB(A)100/m^2)
	Water flow regulation and run off mitigation	Run-off retention (L/m^2)
	Urban temperature regulation	Cooling (UGS fraction: weight)
Cultural ecosystem service	Nature-based recreation	Recreation (Index value/m^2)

Table 2 Description for UGS components

UGS component	Description
Tree	Individual trees or single row of trees, mostly street trees
Woodland	Clustered trees, urban forest (coniferous, non-coniferous and mixed)
Tall shrub	Shrub or hedge height 2–5 m
Short shrub	Shrub or hedge height <2m
Herbaceous vegetation	Low vegetation consisting of non-woody plants, mostly grasses and herbs
Private garden	Land enclosed and associated with private residences and private uses, usually consisting of a mix of vegetation, water and sealed surface
Agricultural land	Arable and horticulture
Water	Inland waterway body, pond, lake
Others	Allotments or community growing spaces, bowling green, camping or caravan parks, cemeteries, golf courses, other sports facilities, playing fields, tennis courts

Table 3 Overview of UES supply rates for individual UGS components

UGS component	UES type					
	Air purification[#] ($g/m^2/yr$)	**Carbon storage (kg/m^2)**	**Noise reduction[#] (dB(A) 100 /m^2)**	**Run-off retention[k,l] (l/m^2)**	**Cooling[m] (UGS fraction: weight)**	**Recreation[#m] (Index value /m^2)**
Tree	3.99[a,b]	28.46[f]	-	9.41	1.00	2.15
Woodland	2.73[b]	28.46[f]	1.125[h]	9.85	1.00	2.90
Tall shrub	2.06[c,d]	14.19[f]	2.000[h,i]	8.08	1.00	2.55
Short shrub	2.06[c,d]	10.23[f]	1.125[h]	8.08	1.00	2.55
Herbaceous	0.91[a,e]	0.15[f]	0.375[h,j]	8.77	0.50	2.55
Private garden	0.83*	0.79[f]	-	6.45	0.50	-
Agricultural land	0.74*	0.10[g]	0.375*	8.30	0.38*	2.35
Water	-	-	-	10.00	-	2.20
Other	0.83*	0.79*	0.375[h]	6.45	0.50	2.35

[a]McDonald et al. (2007); [b]Tallis et al. (2011); [c]Escobedo and Nowak (2009); [d]Baumgardner et al. (2012); [e]Fowler et al. (2004); [f]Davies et al. (2011); [g]Ostle et al. (2009); [h]Fang and Ling (2003); [i]Aertsens et al. (2012); [j]Bolund and Hunhammar (1999); [k]Tratalos et al. (2007); [l]Whitford et al. (2001); [m]Derkzen et al. (2015)
*The rate calculation is based on assumptions of private garden, agricultural land and others (Appendix III).
[#]The rate calculation is weighted on specific buffer zones or boundaries.

Table 4 UES supply capacities in Cheltenham per UGS component type

	UGS component	Area (ha)	% area of total UGS	Relative contribution of UGS components to UES capacities					
				Air purification	Carbon storage	Noise reduction	Run-off retention	Cooling	Recreation
	Tree	237.32	6.32	21.91	41.01	-	7.46	11.21	7.67
	Woodland	278.92	7.43	16.85	48.20	37.91	9.18	13.18	12.17
	Tall shrub	7.43	0.20	0.33	0.64	1.53	0.20	0.35	0.28
	Short shrub	28.10	0.75	1.32	1.75	5.11	0.76	1.33	1.06
	Herbaceous	1,495.45	39.81	29.01	1.36	42.12	43.81	35.33	57.60
	Private garden	1,092.40	29.08	20.53	5.24	-	23.54	25.81	-
	Agricultural land	260.42	6.93	4.10	0.16	7.24	7.22	4.68	8.94
	Water body	12.81	0.34	-	-	-	0.43	-	0.51
	Others	343.54	9.15	5.94	1.65	6.10	7.40	8.12	11.79

Appendices

Appendix I - Table A1-1 Data source and description of UGS components

UGS component	Description	Database	Source file name	Data type	Year	Remarks
Tree	Individual tree or single row of trees, mostly street trees	High Resolution (25cm) Vertical Aerial Imagery © Getmapping Plc	so9020-9023_rgb_250 so9120-9124_rgb_250 so9120-9124_rgb_250 so9217-9226_rgb_250 so9319-9326_rgb_250 so9418-9425_rgb_250 so9518-9525_rgb_250 so9617-9625_rgb_250 so9717-9724_rgb_250 so9818-9822_rgb_250 so9920-9922_rgb_250	JPG	Oct 2018	Delineation by visual interpretation and cross-checking with Google Street View
Woodland	Clustered trees, urban forest (coniferous, non-coniferous and mixed)	OS Open Map – Local © Crown copyright and database rights 2020 Ordnance Survey	SO_Woodland	Polygon	Oct 2019	Further update made during the mapping of tree
Tall Shrub	Shrub or hedge sized 2–5 m	High Resolution (25cm) Vertical Aerial Imagery © Getmapping Plc	so9020-9023_rgb_250 so9120-9124_rgb_250 so9120-9124_rgb_250 so9217-9226_rgb_250 so9319-9326_rgb_250 so9418-9425_rgb_250 so9518-9525_rgb_250 so9617-9625_rgb_250 so9717-9724_rgb_250 so9818-9822_rgb_250 so9920-9922_rgb_250	JPG	Oct 2018	Delineation by visual interpretation and cross-checking with Google Street View
Short Shrub	Shrub or hedge sized <2m	High Resolution (25cm) Vertical Aerial Imagery © Getmapping Plc	so9020-9023_rgb_250 so9120-9124_rgb_250 so9120-9124_rgb_250 so9217-9226_rgb_250 so9319-9326_rgb_250 so9418-9425_rgb_250 so9518-9525_rgb_250 so9617-9625_rgb_250 so9717-9724_rgb_250 so9818-9822_rgb_250	JPG	Oct 2018	Delineation by visual interpretation and cross-checking with Google Street View

UGS component	Description	Database	Source file name	Data type	Year	Remarks
			so9920-9922_rgb_250			
Herbaceous	Low vegetation consisting of non-woody plants, mostly grasses and herbs	Land Cover Map 2015 © NERC (CEH)	LCM2015_GB Layer [Grassland (acid, calcareous, improved, neutral)]	Geodata base	May 2017	For urban peripheral
		OS MasterMap Greenspace Layer	SO9015_GreenspaceArea SO9020_GreenspaceArea SO9025_GreenspaceArea SO9515_GreenspaceArea SO9520_GreenspaceArea SO9525_GreenspaceArea Layer of primary function: [Public park and garden, Amenity – residential or business, Amenity – transport]	Polygon	Sep 2019	For urban core, excluding those with primary form of woodland, inland water, beach or foreshore and manmade surface
Garden	Land enclosed and associated with private residences and private use, usually consisting of a mix of vegetation, water and sealed surface	OS MasterMap Greenspace Layer © Crown copyright and database rights 2020 Ordnance Survey	SO9015_GreenspaceArea SO9020_GreenspaceArea SO9025_GreenspaceArea SO9515_GreenspaceArea SO9520_GreenspaceArea SO9525_GreenspaceArea Layer of primary function: [Private garden]	Polygon	Sep 2019	
Agricultural land	Arable and horticulture	Land Cover Map 2015 © NERC (CEH)	LCM2015_GB	Geodata base	May 2017	
		Land Cover plus: Crops (2018) © NERC (CEH)	lccm-2018	Geodata base	Dec 2018	
Water	Inland waterway body, pond, lake	OS Open Map – Local	SO_SurfaceWater_Area	Polygon	Oct 2019	
Others	Allotments or community growing spaces, bowling green, camping or caravan park, cemetery, golf course, other sports facility, playing field, tennis court	OS MasterMap Greenspace Layer	SO9015_GreenspaceArea SO9020_GreenspaceArea SO9025_GreenspaceArea SO9515_GreenspaceArea SO9520_GreenspaceArea SO9525_GreenspaceArea Layer of primary function: [Allotments or community growing spaces, bowling green, camping or caravan park, cemetery, golf course, other sports facility, playing field, tennis court]	Polygon	Sep 2019	

Appendix I - Reference

CEH, Centre for Ecology & Hydrology (2017) *Land Cover Map 2015* [FileGeoDatabase geospatial data], Tiles: GB, 1:2500. Available at: https://digimap.edina.ac.uk/environment (Accessed 4 Apr. 2020).

CEH, Centre for Ecology & Hydrology (2018) *Land Cover plus: Crops 2018* [FileGeoDatabase geospatial data], Tiles: GB, 1:2500. Available at: https://digimap.edina.ac.uk/environment (Accessed 4 Apr. 2020).

Copernicus (2020) *Copernicus Sentinel 2 colour infrared (Bands 843)* [TIFF geospatial data], Tiles: so, 1: 20000. Available at: https://digimap.edina.ac.uk/pilot (Accessed 4 Apr. 2020).

Copernicus (2020) '*Corine Land Cover - ESRI FGDB*' [FileGeoDatabase geospatial data], version 2020_20u1. Available at: https://land.copernicus.eu/pan-european/corine-land- cover/clc2018?tab=download (Accessed 4 Apr. 2020).

Getmapping (2018) *High Resolution (25cm) Vertical Aerial Imagery* [JPG geospatial data], Tiles: so9017,so9018,so9019, so9020,so9021,so9022,so9023,so9024,so9025,so9026,so9117,so9118,so9119,so9120,so9121,so9122,so9123,so9124,so9125 ,so9126,so9217,so9218,so9219,so9220,so9221,so9222,so9223,so9224,so9225,so9226,so9317,so9318,so9319,so9320,so932

1,so9322,so9323,so9324,so9325,so9326,so9417,so9418,so9419,so9420,so9421,so9422,so9423,so9424,so9425,so9426,so9517,so9518,so9519,so9520,so9521,so9522,so9523,so9524,so9525,so9526,so9617,so9618,so9619,so9620,so9621,so9622,so9623,so9624,so9625,so9626,so9717,so9718,so9719,so9720,so9721,so9722,so9723,so9724,so9725,so9726,so9817,so9818,so9819,so9820,so9821,so9822,so9823,so9824,so9825,so9826,so9917,so9918,so9919,so9920,so9921,so9922,so9923,so9924,so9925,so9926, 1:500. Available at: https://digimap.edina.ac.uk/aerial (Accessed 4 Apr. 2020).

NAEI, National Atmospheric Emission Inventory 2017 (2019) *UK Emissions Interactive Map* [CSV data]. Available at: https://naei.beis.gov.uk/emissionsapp/ (Accessed 21 Jan. 2020).

Ordnance Survey GB (2019) *Boundary-Line*™ [SHAPE geospatial data], Tiles: GB, 1: 10000. Available at: https://digimap.edina.ac.uk/os (Accessed 4 Apr. 2020).

Ordnance Survey GB (2019) *OS MasterMap Greenspace* [SHAPE geospatial data], Tiles: so91nw,so92sw,so92nw,so91ne,so92se,so92ne, 1:2500. Available at: https://digimap.edina.ac.uk/os (Accessed 4 Apr. 2020).

Ordnance Survey GB (2019) *OS Open Map - Local* [SHAPE geospatial data], Tiles: so, 1: 10000. Available at: https://digimap.edina.ac.uk/os (Accessed 4 Apr. 2020).

Appendix II - Table A2-1 Urban ecosystem sub-areas of Cheltenham

Code	Urban ecosystem type	Sub-area	Ward	Area (ha)
111	Continuous urban fabric	111-01		209.92
112	Discontinuous urban fabric	112-01	Warden Hill Ward	132.36
		112-02	Charlton Kings Ward	141.62
		112-03	Battledown Ward	172.20
		112-04	All Staints Ward	50.06
		112-05	Oakley Ward	100.25
		112-06	Prestbury Ward	168.14
		112-07	Pittville Ward	96.07
		112-08	Swindow Village Ward	123.40
		112-09	Lansdown Ward	96.94
		112-10	Park Ward	141.89
		112-11	Up Hatherley Ward	115.84
		112-12	Leckhanpton Ward	171.01
		112-13	Springbank Ward	143.68
		112-14	St. Peter's Ward	86.86
		112-15	Hesters Way Ward	124.09
		112-16	St. Mark's Ward	128.14
		112-17	Benhall and the Reddings Ward	166.06
		112-18	Charlton Park Ward	197.83
121	Industrial or commercial units	121-01		125.21
		121-02		29.55
141	Green urban areas	141-01		60.07
		141-02		42.28
		141-03		28.56
142	Sport and leisure facilities	142-01		36.92
		142-02		32.45
		142-03		112.85
211	Non-irrigated arable land	211-01		26.16
		211-02		20.42
		211-03		54.80
		211-04		159.73
231	Pastures	231-01		44.73
		231-02		470.10
		231-03		21.58
		231-04		54.93
		231-05		30.55

		231-06		80.01
		231-07		119.54
		231-08		30.96
243	Land principally occupied by agriculture, with significant areas of natural vegetation	243-01		27.86
		243-02		75.96
		243-03		365.96
311	Broad-leaved forest	311-01		24.70
		311-02		9.62
313	Mixed forest	313-01		7.72

Appendix III - Detailed calculations of UES supply rates of UGS components

General methodological assumptions on the calculation of UES supply rate in the absence of specific data

1. The calculation of EUS supply rate for private garden is made according to the fraction of woodland (9%), shrub (11.5%), herbaceous (38%), impervious surface (37%) and other (4.5%) stated in Smith et al. (2005) and Tratalos et al. (2007).
2. The composition of others is also assumed to be the same as the private garden since both types have mixed vegetation (Derkzen et al., 2015).
3. As the types of crop in the UK are mainly short shrub and herbaceous, such as winter/spring wheat & barley, oilseed rape, maize and grass etc. (CEH, 2018), the rate of agricultural land is calculated as the mean of that of short shrub and herbaceous. A further factor of 0.5 is applied to the final rate because most crops would be harvested annually.
4. Water is assumed only providing the UES of runoff retention and recreation.

Air purification

The air purification UES supply rates for different UGS components used in this study are summarised and calculated as shown in the Table A2-1 below.

Table A3-1 Literature data and calculation of air purification UES supply rate

		g PM_{10} captured per m^2 of UGS per year (g/m^2/year)								
	Literature study	**Tree**	**Wood land**	**Tall shrub**	**Short shrub**	**Herbaceous**	**Private garden**	**Agricultural land**	**Water**	**Others**
a	McDonald et al. (2007)	4.6 (West Midlands) 4.4 (Glasgow)								
b	Tallis et al. (2011)	2.96	2.73							
c	Escobedo & Nowak (2009)			3.50 [adjusting value 20 (=5.8+5.7+8.5) to tree]	Same as tall shrub					
d	Baumgardner et al. (2012)			0.63 [adjusting value 4.81 (=1.43+1.45+0.66+0.73+0.54) to tree]	Same as tall shrub					
e	Fowler et al. (2004)					0.91 [1/3 of rate of woodland]				
	Mean	3.99	2.73	2.06	2.06	0.91	0.83[1]	0.74[3]	-	0.83[2]

Carbon storage

The carbon storage UES supply rates for different UGS components used in this study are summarised and calculated as shown in the Table A2-2 below.

Table A3-2 Literature data and calculation of carbon storage UES supply rate

		kg carbon stored per m² of UGS (kg/m²)								
	Literature study	**Tree**	**Woodland**	**Tall shrub**	**Short shrub**	**Herbaceous**	**Private garden**	**Agricultural land**	**Water**	**Others**
f	Davies et al. (2011)	28.46 [(28.06+28.86)/2]	Same as tree	14.19 [(12.35+16.03)/2]	10.23 [(13.79+6.66)/2]	0.15 [(0.14+0.15)/2]	0.79			
g	Ostle et al. (2009)							0.1		
	Mean	28.46	28.46	14.19	10.23	0.15	0.79	0.1	-	0.79[2]

Noise reduction

The noise reduction UES supply rates for different UGS components used in this study are referenced and calculated as shown in the Table A2-3 below.

Table A3-3 Literature data and calculation of noise reduction UES supply rate

		Reduced environmental noise dB(A) per 100m² of UGS (dB(A)100/m²) (range)								
	Literature study	**Tree**	**Woodland**	**Tall shrub**	**Short shrub**	**Herbaceous**	**Private garden**	**Agricultural land**	**Water**	**Others**
h	Fang & Ling (2003)		v	v	v	v				v
i	Aertsens et al. (2012)			v						
j	Bolund & Hunhammar (1999)					v				
	Mean	-	1.125 (0.75–1.50)	2.000 (1.50–2.50)	1.125 (0.75–1.50)	0.375 (0.00–0.75)	-	0.375[3] (0.00–0.75)	-	0.375 (0.00–0.75)

v: sourced from literature

Runoff retention

The run-off interception and infiltration by vegetations and water bodies are estimated by the technique adapted from 2 UK studies, Tratalos et al. (2007) and Whitford et al. (2001) whose studies are based on that by Pandit & Gopalakrishan (1996) originally from the Soil Conservation Service (SCS) (1972). The equation for calculating surface run-off (Pe):

$$Pe = \frac{(P - 0.2S)^2}{P + 0.8S}$$

Where P denotes the precipitation and S the maximum potential retention of catchment of which S is given by:

$$S = \frac{2540}{CN} - 25.4$$

Where CN represents the curve number calculated by the SCS for each combination of land cover and soil type. CNs of all UGS are referenced to that used in Tratalos et al. (2007) except the agricultural land. CN for agricultural land is calculated according to the USDA (1986), the mean CN for the row crops and small grain with straight row and crop residue cover treatment.

A common average run-off occurrence in the UK cities from a 12mm rainfall event is adopted while the run-off coefficient Q is calculated as Pe/P; and then the run-off retention is given out by P X Q (Tratalos et al., 2007; Whitford et al., 2001).

The run-off retention UES supply rates for different UGS components used in this study are calculated as shown in the Table A2-4 below.

Table A3-4 Literature data and calculation of runoff retention UES supply rate

	Curve Number (CN)	Precipitation (P)	Max Potential Retention (S)	Surface Runoff (Pe)	Runoff coefficient (Q)	Runoff Retention
		(mm)	(mm)	(mm)		(L/m2)
Tree	58.0	12.00	18.39	2.59	0.22	9.41
Woodland	55.0	12.00	20.78	2.15	0.18	9.85
Tall shrub	66.0	12.00	13.08	3.92	0.33	8.08
Short shrub	66.0	12.00	13.08	3.92	0.33	8.08
Herbaceous	62.0	12.00	15.57	3.23	0.27	8.77
Private garden	74.5	12.00	8.69	5.55	0.46	6.45
Agricultural land	64.8	12.00	13.83	3.70	0.31	8.30
Water	-	-	-	-	-	10.00
Others	74.5	12.00	8.69	5.55	0.46	6.45

Cooling

The cooling UES supply rates for different UGS components used in this study are referenced and calculated as shown in the Table A2-5 below.

Table A3-5 Literature data and calculation of cooling UES supply rate

		Relative cooling potential per m^2 UGS surface area (UGS fraction: weight)								
	Literature study	**Tree**	**Woodland**	**Tall shrub**	**Short shrub**	**Herbaceous**	**Private garden**	**Agricultural land**	**Water**	**Others**
h	Derkzen et al. (2015)	1.00	1.00	1.00	1.00	0.50	0.50		-	0.50
	Mean	1.00	1.00	1.00	1.00	0.50	0.50	0.38[3]	-	0.50

Recreation

A recreation index is developed by Derkzen et al. (2015) after a comprehensive literature review and the related generalization of people's preference on different UGS (Table A2-6). Derkzen et al. (2015)'s generalization suggests that people give higher preference on

(i) A vegetation landscape over a water landscape;
(ii) higher degree of naturalness; and
(iii) variations and an open structure.

Table A3-6 Recreation index score by Derkzen et al. (2015)

Characteristic		**Score**
Landscape	Vegetation	2.8
	Water	2.2
Naturalness	Urban woodland	3.0
	Park, low vegetation	2.3
	Tree avenue, plaza	1.5

The recreation UES supply rates for different UGS components used in this study are calculated as shown in the Table A2-7 below according to the above index.

Table A3-7 Calculation of recreation UES supply rate

UGS type	Landscape	Naturalness	Mean of Landscape and Naturalness	Recreation index value (Index value/m2)	Recreation index value in park (Index value/m2)
Tree	2.8	1.5	2.15	2.15	4.3
Woodland	2.8	3.0	2.90	2.90	5.8
Tall shrub	2.8	2.3	2.55	2.55	5.1
Short shrub	2.8	2.3	2.55	2.55	5.1
Herbaceous	2.8	2.3	2.55	2.55	5.1
Private garden	-	-	-	-	-
Agricultural land	2.8	1.9*	2.35	2.35	-
Water	2.2	-	2.20	2.20	4.4
Others	2.8	1.9*	2.35	2.35	4.7

*Mean score of 'park, low vegetation' and 'tree avenue, plaza' (see Table A2-6)

Appendix III - Reference

Aertsens, J., De Nocker, L., Lauwers, H., Norga, K., Simoens, I., Meiresonne, L., Turkelboom, F. and Broekx, S. (2012) *Daarom Groen! Waarom U Wint Bij Groen in Uw Stad of Gemeente*. VITO, Mol.

Baumgardner, D., Varela, S., Escobedo, F.J., Chacalo, A. and Ochoa, C. (2012) 'The role of a peri-urban forest on air quality improvement in the Mexico City megalopolis', *Environmental Pollution*, 163, pp. 174-183. doi 10.1016/j.envpol.2011.12.016.

Bolund, P. and Hunhammar, S. (1999) 'Ecosystem services in urban areas', *Ecological Economics*, 29, pp. 293–301. doi 10.1016/S0921-8009(99)00013-0.

CEH, Centre for Ecology & Hydrology (2018) *Land Cover plus: Crops 2018* [FileGeoDatabase geospatial data], Tiles: GB, 1:2500. Available at: https://digimap.edina.ac.uk/environment (Accessed 4 Apr. 2020).

Derkzen, M.L., Teeffelen, A.J.A. and Verburg, P.K. (2015) 'Quantifying urban ecosystem services based on high resolution data of urban green space: an assessment for Rotterdam, the Netherlands', *Journal of Applied Ecology*, 52, pp. 1020-1032. doi 10.1111/1365-2664.12469.

Escobedo, F.J. and Nowak, D.J. (2009) 'Spatial heterogeneity and air pollution removal by an urban forest', *Landscape and Urban Planning*, 90, pp. 102-110. doi 10.1016/j.landurbplan.2008.10.021.

Fang, C.F. and Ling, D.L. (2003) 'Investigation of the noise reduction provided by tree belts', *Landscape and Urban Planning*, 63, pp. 187-195. doi 10.1016/S0169-2046(02)00190-1.

Fowler, D., Skiba, U., Nemitz, E., Choubedar, F., Branford, D., Donovan, R. and Rowland, P. (2004) 'Measuring aerosol and heavy metal deposition on urban woodland and grass using inventories of 210Pb and metal concentrations in soil', *Water, Air and Soil Pollution Focus*, 4, pp. 483–499. doi 10.1023/B:WAFO.0000028373.02470.ba.

McDonald, A.G., Bealey, W.J., Fowler, D., Dragosits, U., Skiba, U., Smith, R.I., Donovan, R.G., Brett, H.E., Hewitt, C.N. and Nemitz, E. (2007) 'Quantifying the effect of urban tree planting on concentrations and depositions of PM_{10} in two UK conurbations', *Atmospheric Environment*, 41, pp. 8455-8467. doi 10.1016/j.atmosenv.2007.07.025.

Ostlea, N.J., Levyb, P.E., Evansc, C.D. and Smithd, P. (2009) 'UK land use and soil carbon sequestration', *Land Use Policy*, 26S, pp. S274-S283. doi 10.1016/j.landusepol.2009.08.006.

Pandit, A. and Gopalakrishnan, G. (1996) 'Estimation of Annual Storm Runoff Coefficients by Continuous Simulation', *Journal of Irrigation and Drainage Engineering*, 122, pp.211– 220. doi 10.1061/(ASCE)0733-9437(1996)122:4(211).

Soil Conservation Service (1972) *SCS National Engineering Handbook*, United States Department of Agriculture. Washington, DC.

Smith, R.M., Gaston, K.J., Warren, P.H. and Thompson, K. (2005) 'Urban domestic gardens (V): relationships between landcover composition, housing and landscape', *Landscape Ecology*, 20, pp. 235–253. doi 10.1007/s10980-004-3160-0.

Tallis, M., Taylor, G., Sinnett, D. and Freer-Smith, P. (2011) 'Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments', *Landscape and Urban Planning*, 103, pp. 129-138. doi 10.1016/j.landurbplan.2011.07.003.

Tratalos, J., Fuller, R.A., Warren, P.H., Davies, R.G. and Gaston, K.J. (2007) 'Urban form, biodiversity potential and ecosystem services', *Landscape and Urban Planning*, 83, pp. 308– 317. doi 10.1016/j.landurbplan.2007.05.003.

USDA, United States Department of Agriculture (1986) *Urban Hydrology for Small Watersheds*. Available at: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf (Accessed 15 May 2020).

Whitford, V., Ennos, A.R. and Handley, J.F. (2001) 'City form and natural process-indicators for the ecological performance of urban areas and their application to Merseyside, UK', *Landscape and Urban Planning*, 57(2), pp. 91–103. doi 10.1016/S0169-2046(01)00192-X.