SCOPING UK URBAN NATURAL CAPITAL ACCOUNT - LOCAL CLIMATE REGULATION EXTENSION

Final Report

For Defra

June 2018

4 City Road
London EC1Y 2AA
t : +44(0) 20 7580 5383
e : eftec@eftec.co.uk
w : www.eftec.co.uk

This document has been prepared for the Department for Environment, Food and Rural Affairs (Defra) by:

Economics for the Environment Consultancy Ltd (eftec)
4 City Road
London
EC1Y 2AA
www.eftec.co.uk

in association with the Centre for Ecology and Hydrology (CEH) and Collingwood Environmental Planning Limited (CEP).

Study team
Jake Kuyer (eftec)
Ian Dickie (eftec)
Laurence Jones (CEH)
Dan Morton (CEH)
Emily Robinson (CEH)
Peter Phillips (CEP)
Sian Morse-Jones (CEP)

Peer reviewer / Reviewer
Kieron Doick (external)
Rob Tinch (eftec)

Acknowledgements:

The study team would like to thank would like to thank members of the steering group and others for the time and effort they have contributed to developing this report: Colin Smith (Defra), Rocky Harris (Defra), Victoria Burch (Defra).

CONTENTS

KEY MESSAGE

The aim of this study is to extend the existing physical and monetary analysis of local climate regulating benefits of natural capital in urban areas to cover a greater portion of Great Britain. This work will enable Defra and ONS to make further progress in developing a full set of natural capital accounts for the UK in line with the 2020 Natural Capital Accounting Roadmap.

Overall the key contribution of the study is to demonstrate and test the feasibility of developing estimates of local climate regulating benefits of urban natural capital at the GB scale, and assess how this could be refined in the future. As an addendum to the Scoping report (eftec *et al.*, 2017), this report primarily is focused on the following three factors addressed by the extension to the accounts:

1. Improve accounting of spatial differentials in climate – incorporate better evidence on the spatial pattern of temperatures above critical thresholds across the country and summarise these to areas of appropriate spatial scale to match to Gross Value Added (GVA) data at city region. This requires spatial boundary information to be obtained.
2. Blue space assessment – review the literature to find estimates of the temperature differentials (i.e. reduction) due to the existence of blue space (rivers, lakes, canals).
3. Other green space categories – review the literature to find estimates of temperature differentials for other types of green space (the original scoping study only considered parks and woodlands) such as private gardens; and consider and identify methodological options for physical flow calculations that can account for the fact that these categories of green space (e.g. private gardens) are often comprised of many small patches (i.e. smaller than the minimum size threshold used in the scoping study).

Findings

The physical account measures the cooling effect provided by the environmental asset. In terms of the Common International Classification of Ecosystem Services (CICES) Version 5.1, this relates to the ecosystem service 'regulation of temperature and humidity including ventilation and transpiration' which is defined thus: *"regulating the physical quality of air for people"* and *"mediation of ambient atmospheric conditions (including micro and mesoscale climates) by virtue of the presence of plants"* (CICES, 2018). The table below shows the cooling effect in each of the 11 city regions in aggregate, and broken down by greenspace and bluespace feature. The combined average cooling effect is relatively stable across city regions, between 0.63 degrees Celsius, and 0.88 degrees Celsius[1] as per the table below. For all city regions, greenspace provides greater overall cooling than bluespace, however the relative contribution of woodland, parks and grassland, and gardens varies between them.

City Regions	Cardiff	Edinburgh	Glasgow	Greater Manchester	Liverpool	London	North East	Sheffield	West Midlands	West of England	West Yorkshire
Combined	**-0.71**	**-0.88**	**-0.80**	**-0.75**	**-0.63**	**-0.72**	**-0.65**	**-0.73**	**-0.72**	**-0.69**	**-0.83**
Woodland	-0.23	-0.39	-0.32	-0.24	-0.15	-0.25	-0.17	-0.23	-0.21	-0.19	-0.28
Parks / grass	-0.20	-0.24	-0.22	-0.27	-0.19	-0.21	-0.22	-0.20	-0.21	-0.19	-0.32
Gardens	-0.26	-0.24	-0.24	-0.22	-0.28	-0.24	-0.25	-0.29	-0.28	-0.29	-0.22

[1] Note that this increase from the scoping study is primarily because the Natural Capital considered now includes more categories, most importantly gardens as well as blue space.

Rivers / canal	-0.01	-0.01	-0.02	-0.01	-0.01	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01
Lakes / ponds	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

The monetary account measures the value of the benefit provided expressed in pounds. The cooling effect is monetised as the cost savings from air conditioning and the avoidance of labour productivity loss due to heat. The cost savings from air conditioning are calculated based on a value found in the literature for London; a corresponding value is then applied to each city region based on the relative proportion of their air conditioned floorspace to London's. The avoided loss of labour productivity is monetised as the GVA that would have been lost due to additional heat stress in the absence of the cooling effect.

The monetary account of the future provision of the ecosystem service, or future benefit stream, accounts for the benefits received over a specified time period, in this case 100 years. This benefit stream accounts for the annual value projected over time factoring in any known trends which will affect the physical flow or monetary value of the benefits, and discounting the value stream to be presented in present days value, or Net Present Value. The account incorporates a projection for an annual increase in working day productivity losses due to climate change which increases the value of urban cooling over time.

The table below shows the results from the annual monetary account and present values of the future benefits stream for each of the 11 city regions. The size of the monetary value tracks to the size and structure of the city region's economy, with southern cities such as London also being subject to a greater number of hot days mitigated through the cooling effect of urban natural capital. The valuation results are dependent on the size of the effect being mitigated (i.e. hot days), which is subject to fluctuate year on year. This iteration of the accounts is based on a five year average number of hot days in each temperature band, between 2012 and 2016.

City Regions	Cardiff	Edinburgh	Glasgow	Greater Manchester	Liverpool	London	North East	Sheffield	West Midlands	West of England	West Yorkshire
Annual value - £'000s	£1,453	£135	£141	£4,150	£1,740	£139,863	£187	£2,274	£9,286	£3,363	£3,049
100 year NPV - £million	£118	£28	£31	£352	£160	£9,038	£33	£222	£632	£245	£297

The total values for the 11 city regions shows the considerable the cooling effect provided by urban natural capital. For 2016, which experienced an above average number of hot days, the total value of the service was £274m, of which the London City Region accounted for £233m.

	2012 - 2016 average	Service value in 2016
Annual value	£166,000,000	£274,000,000
100 year NPV	£11,156,000,000	

The extension of the local climate change account demonstrates an approach to incorporating urban blue space, small green space patches (e.g. private gardens), and greater spatial granularity into the accounts which provide a more in depth understanding of the impact of this benefit from urban natural capital. Considerable benefit arises through the reduction of air conditioning costs and avoidance of labour productivity losses due to heat in physically intensive jobs. The overall value of urban green and blue space across all 11 city regions is found to be £166 million annually, or £11.2 billion present value over the 100 year asset life. Further refinement of the accounts could provide greater robustness, and some recommendations for subsequent iterations follow.

Recommendations

The modelling of local climate regulation services from urban bluespace (rivers/canals, and lakes/ponds/reservoirs and additional greenspace (gardens) features marks an important development over the work done in the earlier scoping study (eftec *et al.*, 2017), principally as it broadens out the scope of the urban natural capital assets that have been assessed. Similarly, to the earlier scoping work however, there are several caveats and limitations to the approach that could be addressed to improve the accuracy and robustness of the values emerging from the analysis. Key recommendations for this are outlined below.

Literature review to further refine the cooling effect values. A key limitation of the modelling approach used in this study is the relevance / applicability of the cooling effect values for different urban bluespace and greenspace features (and their buffer zones / 'distance decay' effect) used in the physical account modelling. This is a particular issue for non-linear bluespace features (lakes / ponds / reservoirs) where the best available evidence from O'Malley *et al.* (2015) was: (a) theoretical / simulation based; (b) somewhat unclear in terms of the exact nature of the polygon features that were assessed; and (c) did not include any values for the cooling effect adjacent to the features (i.e. 'distance decay' within the buffer zone). Also, the values used for linear features were from one empirical study looking at a specific UK river and therefore not canals. To address these limitations, a ***systematic literature review***[2] should be undertaken to, as far as possible, obtain robust, empirical cooling values for specific linear (river / canal) and other (lake / pond / reservoir) urban bluespace features, and for greenspace features such as private gardens, for which minimum size thresholds and distance decay-effects within buffer zones have not been studied, specific to the UK context. This should include consideration of size thresholds with specific cooling values obtained for different size / width classes of feature, to allow for more granular physical account modelling, similar to that adopted in the scoping study for urban woodlands and parks (eftec *et al.*, 2017). In summary, the systematic literature review should seek to obtain robust values for all classes of urban bluespace feature for all of the indicators listed in Table 2.

Consideration of seasonality effects. While cooling provided by natural capital is a recognised benefit in summer, the effects of natural capital in winter are largely more uncertain. Trees can prevent radiative heat loss from the ground in winter, thereby reducing frost and ameliorating local winter temperatures, but may also reduce warming of the ground by weak winter sunlight. These and other processes may have both positive and negative impacts on winter energy use for domestic heating, which has not been studied in the UK. However, the i-Tree Eco software developed by the US Forest Service does assess seasonality aspects within its 'energy effects' module[3]. Although this aspect of i-Tree Eco is not well calibrated for the UK context (due to different building construction practices in the US and the UK), it could potentially be used to provide a relatively crude assessment of seasonal cooling / warming provided by natural capital.

Commission empirical research to fill remaining gaps. Following the outcomes of the literature review discussed above, any critical outstanding gaps in the evidence base concerning cooling values

[2] As a systematic review of the literature was not conducted for this study it is unknown whether substantial literature on these values exists, or whether there is a genuine gap in understanding that needs to be filled with original research.

[3] https://www.itreetools.org/eco/overview.php

for different urban bluespace (i.e. the indicators in Table 1) and greenspace features should be addressed via new empirical research undertaken in the UK context.

Value of air condition cost and carbon savings. A refined approach to estimating the cost savings from reduced air conditioning use due to urban cooling may improve the accuracy of the estimate of these savings. Greater understanding is needed of the air conditioning usage in the city regions, in particular the degree to which air conditioning capabilities are present (likely declining towards the more northern regions), and how usage responds to changes in temperature, especially at the temperature ranges towards the lower usage thresholds, which was not considered in this study (i.e. 20ºC >< 28ºC). Demand will also vary according to the residential and economic makeup of the city regions, which also may shift along with changing climate. Energy use should also be investigated, as urban vegetation humidifies air, which impacts on the efficiency of some types of air conditioning unit. Additionally, the cost of carbon associated with the energy production for air conditioning could also be investigated.

Adoption of a more granular, bottom-up approach to physical account modelling. Evidence shows that particularly in the case of linear bluespace features (rivers / canals) there is potential to adopt a more granular / bottom-up assessment of different cooling effects (T_{urban} – T_{blue} in ºC) accounting for variation in urban form and design along the corridor associated with the linear features (see section 2.2 for an explanation of relevant concepts). This approach was beyond the scope of the current study due to the GIS processing required (e.g. processing of detailed spatial indicators of urban form in order to characterise and delineate different segments of the river / canal corridor). The key conceptual assumption here is that cooling values (i.e. T_{urban} – T_{blue} in ºC) in the river / canal corridor will vary depending on the nature of the urban form in the corridor. This concept was evidenced empirically for the River Don (Sheffield, UK) in Hathway and Sharples (2012). Although not identified specifically in the evidence review, this concept is also likely to be relevant to other bluespace features (lakes, ponds etc) and greenspace features as well (parks, urban woodland etc), especially due to prevailing wind deformation of the cooling boundary[4]. In relation to linear bluespace features, in principle a more granular, bottom-up assessment of cooling in the river corridor could be undertaken that takes this into account. The main constraint is the GIS analysis required to assess and categorise urban form typology in the river corridor, particularly if this is to be conducted at national scale. A sequence of possible steps for conducting this type of more bottom-up analysis are outlined below:

1. GIS analysis to model and delineate spatially the extent (i.e. segments of the river corridor) that can be allocated to a typology of urban form. For example, interactions between urban form and cooling for the River Don (Sheffield, UK) have distinguished between ‘open square’, ‘open street’, ‘closed street’ and ‘enclosed’ categories within an overall typology of river corridor urban form (see Hathway & Sharples 2012). Spatial delineation by economic activity could also inform more refined estimates of impact on productivity.
2. Calculate the area (absolute) and percentage of the buffer (i.e. river corridor) comprised of different categories of urban form from the typology in (1) – the percentage values (%) would be for whichever geography was being assessed in the account (e.g. whole of the UK, a specific city).
3. Calculate net values for buffer T_{urban} – T_{blue} in ºC based on the values for different urban form categories. There is some UK-based empirical data on cooling effect within the river corridor under different types of urban form in Hathway and Sharples (2012). The same proportional approach as per steps (3) and (4) in the physical flow account (see section 3.3) would then be applied to ascertain the net cooling effect of linear bluespace

[4] As pers. comm. Kieron Doick, 2018.

features based on the range of cooling values provided given different urban form / design conditions within the river corridor.

Expand the urban extent beyond the 11 city regions. A future study should seek to incorporate a greater proportion of GB's urban extent. Ideally this would make use of real data, but alternately a means of uplifting could be applied with reasonable confidence with calibration.

Monitor trends in temperature, and the impact that they have on the value of natural capital. As the model is focused on investigating the avoided impact of hot days, the number of hot days in a given year plays a big factor in the overall value of the natural capital asset on any given year. By updating the model on a regular basis, the effect of these temperature trends on the overall value of natural capital can be monitored and tracked over time. This is particularly relevant in the context of climate change, and a more robust approach to estimating the future impact of climate change on productivity, and the ability of natural capital to mitigate this, would improve the accuracy of the model.

1. INTRODUCTION

1.1. Context

The aim of this study is to extend the existing physical and monetary analysis of local climate regulating benefits of natural capital in urban areas to cover a greater portion of Great Britain (GB). This work will enable Defra and ONS to make further progress in developing a full set of natural capital accounts for the UK in line with the 2020 Natural Capital Accounting Roadmap.

Achieving this ambitious objective requires addressing both conceptual and practical challenges in the process of estimating and reporting the ecosystem service flows associated with UK urban natural capital. Inevitably the present work is subject to gaps in both scientific understanding of urban ecosystems and the availability of data and methods. Overall the key contribution of the study is to demonstrate and test the feasibility of developing estimates of local climate regulating benefits of urban natural capital at the GB scale, and assess how this could be refined in the future.

Activities for this extension focused on establishing the approach and data to be used to extend the analysis of urban local climate regulation, as an addendum to the Scoping report (eftec *et al.*, 2017)[5], this report primarily is focused on the following three factors:

1. Improve accounting of spatial differentials in climate – incorporate better evidence on the spatial pattern of temperatures above critical thresholds across the country and summarise these to areas of appropriate spatial scale to match to GVA data at city region. This requires spatial boundary information to be obtained.
2. Blue space assessment – review the literature to find estimates of the temperature differentials (i.e. reduction) due to the existence of blue space (rivers, lakes, canals).
3. Other green space categories – review the literature to find estimates of temperature differentials for other types of green space (the original scoping study only considered parks and woodlands) such as private gardens; and consider and identify methodological options for physical flow calculations that can account for the fact that these categories of green space (e.g. private gardens) are often comprised of many small patches (i.e. smaller than the minimum size threshold used in the scoping study).

1.2. Report structure

The remainder of this report is structured as follows:

Section 2	Scope: the natural capital accounting framework, the boundary of the urban area and the natural capital assets included within the account.
Section 3	Method: the steps undertaken to develop the initial UK urban natural capital account for local climate regulation, including the approach to quantifying and valuing natural capital stocks and flows.
Section 4	Results and discussion: proof-of-concept physical and the monetary accounts for UK urban areas for local climate regulation.

[5] Note that not all references relevant to urban cooling are included in this report, but are retained in the original scoping study

Section 5 Conclusions and recommendations: the application (purpose) of the urban natural capital account for local climate regulation, along with the current limitations of data and potential future refinement of the accounts.

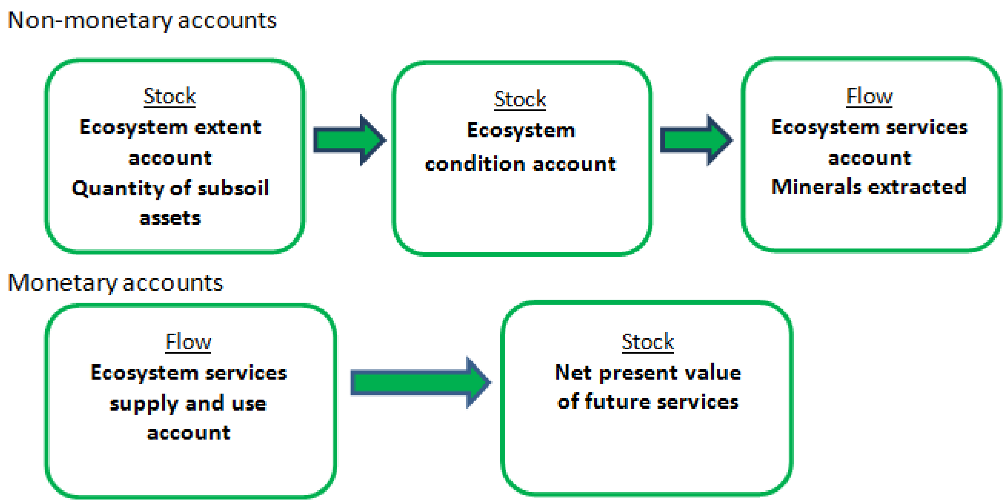
The report is accompanied by an Excel file providing detail on the data sources, assumptions, method steps and calculations that underpin this urban natural capital account for local climate regulation.

2. SCOPE

2.1. Natural capital accounting framework

Defra and ONS (2017) outline the key principles and framework structure to be followed when developing natural capital accounts in the UK as part of the ONS Environmental Accounts. The framework features two main types of account: (i) stock (assets) accounts which capture information on the natural capital assets (e.g. freshwaters, grasslands) and (ii) flow (ecosystem services) accounts which report information on the annual benefits produced by the natural capital assets (e.g. recreation, climate regulation). Both stock and flow accounts are made up of several accounting schedules that record monetary or physical (non-monetary) benefits, as shown in Figure 1.1. An account is developed by collating and analysing financial, economic, social and environmental data on natural capital across the UK, including via the use of Geographical Information Systems (GIS).

Figure 1.1 The framework of national natural capital accounting schedules (Defra/ONS, 2017)



This study has developed an account for the local climate regulating effects of urban bluespace and greenspace. In terms of the Common International Classification of Ecosystem Services[6] (CICES) Version 5.1, this relates to the ecosystem service 'regulation of temperature and humidity including ventilation and transpiration' which is defined thus: *"regulating the physical quality of air for people"* and *"mediation of ambient atmospheric conditions (including micro and mesoscale climates) by virtue of the presence of plants"* (CICES, 2018). For the purposes of developing this account, the scope of each account is defined as follows:

1. **Physical account of natural capital extent** (stock account):

2. **Physical account of natural capital condition** (stock account):

3. **Physical account of ecosystem service provision** (flow account):

4. **Monetary account of annual provision of ecosystem service** (flow account):

5. **Monetary account of future provision of ecosystem service** (stock account):

[6] CICES (Common International Classification of Ecosystem Services) is a classification of ecosystem services developed from the work on environmental accounting undertaken by the European Environment Agency (EEA) that is based on the well-established split into provisioning, regulating and cultural services (supporting services are not included because CICES focuses on final services to humans).

2.2. Natural capital assets

This section covers assets that were not considered in the previous scoping study (eftec *et al.*, 2017), and are an extension to that work; namely, urban bluespace assets and urban private garden assets. In general the scope of this extension study is focused on the assets which were not covered in the previous work.

Urban bluespace assets

The text below introduces the main scientific and policy concepts underpinning calculations in the local climate regulation physical account (asset extent, flows of ecosystem services) in relation to the cooling effect of urban bluespace (this ecosystem service is defined at section 2.1 above by way of the CICES framework). Bluespace was not considered within the previous scoping study (eftec *et al.*, 2017), hence the need to review and synthesise these concepts here.

Defining urban bluespace assets

UK planning policy includes some limited consideration of urban bluespace from which general definitions can be drawn. For example: (1) the National Planning Policy Framework (NPPF) for England provides a definition of open space covering *"all open space of public value, including not just land, but also areas of water (such as **rivers, canals, lakes and reservoirs**)"* (DCLG, 2012 p.54)[7]; and (2) Planning Advice Note 65 (PAN65) in Scotland includes the seemingly broad concept of *"open water"* as a sub-category within the PAN65 typology *"natural / semi-natural greenspace"* (Scottish Government, 2008 p.20)[8] although the focus on natural / semi-natural aspects may preclude consideration of some urban bluespace assets with built capital components (e.g. reservoirs, canals), which are considered bluespace for the purposes of this study.

The academic literature reviewed includes some more general definitions such as the following from Gunawardena *et al.* (2017 p.8): *"all substantial bodies of static or dynamic water found in urban areas"*. Policy definitions therefore include some specific (NPPF) and more general aspects (PAN65) whereas the academic definition introduces qualitative aspects associated with the size of the feature (the notion of *"substantial"*) and its flow (both *"static"* and *"dynamic"*). These qualitative aspects are discussed further below in relation to the different factors that can influence the ability of urban bluespace assets to provide a cooling effect.

The cooling effect of urban bluespace and the cooling mechanisms involved

Studies have shown that urban bluespaces have a cooling effect (T_{urban} - T_{blue} in ºC) whereby urban water bodies (and the adjacent air temperature) are cooler than the surrounding area or other non-waterbody locations in the same town / city at the same point in time (Volke *et al.* 2013 after Bowler *et al.*, 2010).

It is understood that urban bluespace provides cooling to the surrounding area via the following mechanisms: (1) cooling effect of evaporation from the waterbody; (2) absorbing heat, especially where the water body has a large mass; and (3) the dynamic process of transporting heat out of an area by moving it, for example, rivers (Kleerekoper *et al.*, 2012). Various empirical and theoretical values for the cooling effect of urban bluespace are discussed further below and in Table 2.

Factors influencing the cooling effect of urban bluespace

Evidence shows that the ability of urban bluespace to modify the temperature of surrounding areas is influenced by a range of factors, many of which can be linked to the context / location of the feature, in both local and regional terms. Factors identified in the literature review include:

[7] Accessible from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/6077/2116950.pdf

[8] Accessible from: http://www.gov.scot/Resource/Doc/225179/0060935.pdf

- ***Physical characteristics of the blue space***, for example, waterbodies with large surface areas, or that flow are likely to be more effective at cooling (Kleerekoper *et al.*, 2012). In relation to rivers, the rate at which the heat absorbed by a river will be carried away depends on the river dynamics (Hathway and Sharples, 2012). Further, the albedo of a river will change depending on the quantity of suspended particles – intense rain events which may result in large stormwater inputs to rivers may impact albedo on a daily or even yearly basis (ibid). The depth and volume of the waterbody will also play a role in its capacity to absorb heat, and there is also some evidence that the shape of the waterbody can influence cooling (Sun *et al.*, 2012);
- ***Weather circumstances and ambient air temperature***. The level of cooling provided by the waterbody increases at higher temperatures (Hathway and Sharples, 2012; Kleerekoper *et al.*, 2012), though this effect is determined by seasonality also (see below). Wind direction can also exert an influence – the cooling effect of waterbodies is greater on their leeward side as cooler air above the waterbody is transferred by the wind (Santamouris *et al.*, 2016);
- ***Climate***. Dry, hot climates may have increased evaporation cooling potential of waterbodies relative to the UK (Santamouris *et al.*, 2016), though the seasonality effect may be more pronounced in this case (see below);
- ***Season***. An empirical study from the UK showed that cooling provided by rivers notably diminishes between spring and summer, when river water temperature is warmer (Hathway and Sharples, 2012). Importantly, waterbodies are susceptible to drought which can reduce the effectiveness of all bluespace cooling mechanisms at critical times (Coutts *et al.*, 2014 cited in Filho *et al.*, 2018);
- ***Time of day***. An empirical study from the UK found the cooling effects of urban rivers to be greatest in the morning, with no significant cooling in the night (Hathway and Sharples, 2012). It has also been reported that urban waterbodies can actually contribute to increased temperatures after sunset in the late summer when surface waters are relatively warm (Steeneveld *et al.*, 2014);
- ***Urban form or design*** may influence the distribution of cooling from waterbodies (i.e. the 'distance decay' effect – see below). For example, the characteristics of urban form along the river bank can affect cooling distribution away from the bank (Hathway and Sharples, 2012) by shading the waterbody or affecting wind flow (Gunawardena *et al.*, 2017; Manteghi *et al.*, 2015). Hathway and Sharples (2012) found greater cooling (at approximately 30m from river) as street canyons opened up, providing access to the river; and
- ***Distance decay***. The cooling provided by urban waterbodies is typically highest over the centre of the feature, declining with distance ('distance decay') as a function of several of the interrelated factors described above (e.g. physical characteristics of the waterbody, urban form / design in the river corridor). An empirical study from the UK showed that cooling from an urban river can extend 30-40m from the centre of the river (where the surrounding urban form is open), with a distance decay effect of approximately 30%, 60% and 80% less cooling at distances of approximately 10m (or 0m), 30m (or 20m) and 40m (or 30m) from the river centre (or river bank) respectively (see Hathway and Sharples, 2012). The river in this case was 22m wide. Studies from temperate climates elsewhere in the world (Japan) have reported cooling effects extending to 50-400m from the bank of a river 270m wide (Murakawa *et al.*, 1991 in Manteghi, 2015) and for ponds with an area of 127,000m^2, as far as 400m (Ishii *et al.*, 1991 in Manteghi, 2015).

Empirical and theoretical cooling values for urban bluespace

Various cooling values for urban bluespace have been extracted from the literature reviewed. These are presented below in Table 2 organised by the different categories of urban bluespace identified in the policy and literature review (see above). A distinction is made between values obtained via empirical measurements and simulations (i.e. theoretical / modelled values). Based on the factors listed above that influence cooling, optimal values for modelling the cooling effect of urban bluespace in a UK context have been selected. These have been used in the physical account calculations (see sections 3.1 and 3.3). Values have been extracted for the variables / indicators listed in Table 1 below.

Table 1: Indicators used in the local climate regulation physical flow account bluespace modelling

Indicator[9]	Unit
Minimum size threshold (width) for **linear** bluespace features (rivers / canals) over which a cooling effect is assumed to occur	Metres (m)
Minimum size threshold (area) for **polygon** bluespace features (lakes / ponds / reservoirs) over which a cooling effect is assumed to occur	Square metres (m^2)
Buffer size for **linear** bluespace features (rivers / canals) to establish the maximum distance from bankside over which a reduced cooling effect (i.e. distance decay) is assumed to occur	Metres (m)
Buffer size for **polygon** features (lakes / ponds / reservoirs) to establish the maximum distance from bankside over which a reduced cooling effect (i.e. distance decay) is assumed to occur	Metres (m)
Cooling effect (T_{urban} - T_{blue}) for the **area encompassed by linear** bluespace features (rivers / canals)	Degrees centigrade (ºC)
Cooling effect (T_{urban} - T_{blue}) for the **area encompassed by polygon** bluespace features (lakes / ponds / reservoirs)	Degrees centigrade (ºC)
Cooling effect (T_{urban} - T_{blue}) for the **buffer area associated with linear** bluespace features (rivers / canals)	Degrees centigrade (ºC)
Cooling effect (T_{urban} - T_{blue}) for the **buffer area associated with polygon** bluespace features (lakes / ponds / reservoirs)	Degrees centigrade (ºC)

Table 2: Cooling effect values for urban bluespace extracted from literature reviewed

Type of blue space	Issues / limitations / comments	Cooling effect (ºC) - for day time air temp unless otherwise stated[10]	Source
Generic urban bluespace			
Urban water	Scientific basis for the differential not reported. Seems to be based on review of two studies - Robitu *et al.* (2004) and Nishimura *et al.* (1998), also reported below.	Average cooling effect of 1-3ºC to extent of 30-35m	Kleerekoper *et al.* (2012)
Various urban blue space such as ponds, lakes or rivers	Meta-analysis of 27 studies (including remote sensing) reporting air temperatures at various types of urban blue space such as ponds, lakes or rivers and compared them with reference sites at defined distances or to urban reference sites in the same city	Cooling effect on average of 2.5ºC relative to context.	Volker *et al.* (2013)
Rivers			

[9] The literature review suggests that the cooling effect in the buffer area associated with bluespace features is variable as a function of distance from the feature. However, for the purposes of the physical account modelling, a simple binary cooling effect (on / off), with one value, has been used as a reasonable compromise given the level of complexity possible within the scope of this project.

[10] The mean cooling value is the mean of the various cooling values presented in a given source. This generally relates to the mean of temperature measurements taken at different locations across a study site, in terms of different built environment / urban design context or distances from the bluespace feature. The max cooling effect describes the highest value recorded at a given location.

Type of blue space	Issues / limitations / comments	Cooling effect (°C) - for day time air temp unless otherwise stated[10]	Source
Small urban river in UK: River Don in Sheffield. Average flow of 4.7 m^3/s. Channel approx. 22m wide. Sheffield has mean Urban Heat Island (UHI) intensity of 2°C on spring day.	**Empirical study** based on field survey data. Focus on small rivers. Level of cooling related to ambient air temp, increasing at higher temps. Seasonal differences (differential reduced in summer when the river water temperature was warmer)	Average cooling of 1°C over the river during ambient temp greater than 20°C. On hot days in May, 2°C cooling over the river and 1.5°C cooling on river bank during the day (no cooling evidence at night)	Hathway and Sharples (2012)
Ota River, Hiroshima, Japan (270m wide).	Downwind cooling influences from river extend at least a few hundred metres. Local cooling more widespread when lower building density and wider streets	Air temp around river 3-5°C cooler between 12-5pm on fair days	Murakawa *et al.* (1991) cited in Manteghi *et al.* (2015)
Channelled Stream inside central district, Seoul, South Korea	Impact of stream restoration. Temperature compared between urban district with restored stream versus urban district 200m away. Measured before during and after stream restoration during August over 3 years	Restored stream district, average 0.6-1 °C cooler than the district 200m away	Kim *et al.* (2008) - cited in Manteghi *et al.* (2015)
Ponds, pools and lakes			
An urban matrix of pools and ponds in Seagrave, London (UK). Project area of 7150 m^2. Area of waterbodies within this of 700 m^2.	Theoretical study (**simulation based**). Location characterised by low density buildings and open spaces. Max design temperature 25.6°C	Mean temp decrease 0.1°C. Max temp decrease 0.4°C	O'Malley *et al.* (2015) cited in Santamouris *et al.* (2016)
Pools, ponds & fountains in Toulouse, France	Theoretical study (**simulation based**). Location characterised by Low density buildings and open space Max design temperature 29°C	Mean temp decrease 2°C. Max temp decrease 6°C.	Martins *et al.* (2016) cited in Santamouris *et al.* (2016)
Pond 4m x 4m in Bucharest		1°C measured at height of 1m, at 30m distance	Robitu *et al.* 2004 cited in Kleerekoper *et al.* (2012)
Pools in Pavones, Fontarron and Horcajo Madrid, Spain	Theoretical study (**simulation based**). Location characterised by high density buildings with open spaces. Max design temperature 29°C	Mean temp decrease 1.5°C. Max temp decrease 2.6°C.	Tumini (2014) cited in Santamouris *et al.* (2016)
Open waterbody in European Fictitious City	Theoretical study (**simulation based**). Location characterised by urban zone. Max design temperature 25°C	Mean temp decrease 0.5°C. Max temp decrease 1.7°C.	Theeuwes *et al.* (2013) cited in Santamouris *et al.* (2016)
Pools and Ponds in Salonica, Greece	Theoretical study (**simulation based**). Location characterised by high density buildings with open spaces. Max design temperature 40.9°C	Mean temp decrease 1.9°C. Max temp decrease 7.1°C.	Chadzidimitriou *et al.* (2013) cited in Santamouris *et al.* (2016)

Type of blue space	Issues / limitations / comments	Cooling effect (°C) - for day time air temp unless otherwise stated[10]	Source
Pond 100m wide in an urban park in Tel Aviv, Israel		1.6°C at midday	Sarroni and Ziv (2003) cited in Manteghi *et al.* (2015)
Pond in central park of Fukuoka city, Japan	Temperatures compared for the pond filled versus a water drained situation were compared to the urban matrix reference sites, to calculate the magnitude of the cooling effect	Average temp inside park 0.4°C cooler with pond filled. Average temp of residential area surrounding park 1.2°C cooler with pond filled.	Ishshii *et al.* (1991) cited in Manteghi *et al.* (2015)
Pools and ponds in Portland, USA	Theoretical study (**simulation based**). Urban Zone. Max design temperature 27°C	Mean temp decrease 0.3°C. Max temp decrease 1.1°C.	Taleghani *et al.* (2014a) cited in Santamouris *et al.* (2016)

Urban private garden assets

The text below introduces the main scientific and policy concepts underpinning calculations in the local climate regulation physical account (asset extent, flows of ecosystem services) in relation to the cooling effect provided by urban private gardens. Private gardens were not considered within the previous scoping study (eftec *et al.*, 2017), hence the need to review and synthesise these concepts here.

Defining urban private garden assets

UK planning policy includes several references to private or residential gardens. Though the NPPF does not define private gardens, it does set out various principles and policy justification explaining why these assets should be protected such as *"…resist[ing] inappropriate development of residential gardens, for example where development would cause harm to the local area"* (DCLG, 2012 p.14). PAN65 in Scotland does include an explicit definition of 'private gardens or grounds' as part of the typology of openspace described in the PAN: *"areas of land normally enclosed and associated with a house or institution and reserved for private use"* (Scottish Government, 2008 p.5). PAN65 goes on to split the 'private garden or grounds' category into three discrete sub-categories as follows: (i) private gardens; (ii) school grounds; and (iii) institutional grounds.

Interestingly, PAN65 does not describe the use of private gardens beyond the fact that they are reserved for *"private use"* nor does it give any indication of the type(s) of land cover, vegetation etc that one might commonly expect to find in private gardens. In natural capital terms therefore, this definition arguably means that a private garden could be wholly or partially comprised of built capital (slabs, decking other forms of hardstanding etc) yet still considered as a 'garden'. Clearly a garden comprised of mainly built capital would provide fewer ecosystem services, especially local climate regulation which is highly dependent on vegetation as discussed in the next section.

The academic literature elaborates on definitions of private gardens somewhat, for example, Zardo *et al.* (2017) list several types of feature that could be described as gardens (e.g. private gardens, domestic gardens, community gardens, backyards, vegetable gardens). Cameron *et al.* (2012) include a definition that is very close to that of PAN65, with the exception that they qualify tenure as being either privately owned or rented.

The extent and cooling effect of urban private gardens assets

Private gardens are a critical urban natural capital asset given their prevalence across UK cities. For example, it is reported that 87% of UK households have access to a private garden (Gibbons *et al.*, 2011 cited in Cameron *et al.*, 2012) with domestic garden size in UK cities reportedly varying between $3.6m^2$ and $2290m^2$ (Loram *et al.*, 2007 cited in Cameron *et al.*, 2012).

It is anticipated that urban private gardens may contribute to local climate regulation although there is a paucity of empirical data to evidence this assertion (Cameron *et al.*, 2012). In general, studies on urban natural capital and green infrastructure have found it difficult to robustly assess the ecosystem services provided by private gardens, principally due to a lack of high resolution data (Claessens *et al.*, 2014).

A critical feature of private gardens is that they are highly heterogenous in terms of their form and function (e.g. as they are under predominantly private control – see above) and their surrounding context (e.g. urban form / design), all of which may influence the consistency with which they are able to provide local climate regulation services (Cameron *et al.*, 2012). For example, a study of community gardens in California (Lin *et al.*, 2018) found that mean air temperature above garden beds is significantly influenced by local scale issues (e.g. characteristics of the garden, size, age), vegetation type (e.g. tree / shrub richness, tallest vegetation) and landscape scale factors (e.g. percentage of urban land cover within a 2km buffer). A study from Florence (Italy) suggested that the cooling effect of a small urban courtyard with trees was a function of the tall trees but also the result of shading by taller buildings that overlooked the courtyard (Bacci *et al.*, 2003).

Empirical and theoretical cooling values for urban private gardens

Within the scope of the literature review undertaken, very few studies were identified which report cooling effects (T_{urban} - $T_{private\_garden}$ in ºC) for urban private gardens. Further, it is unclear in many of the sources reviewed whether the studies relate to private / domestic gardens as opposed to communal gardens and / or urban parks (this distinction is important as the different asset classes are likely to have different vegetation characteristics and therefore different cooling effects, hence the concern about conflating communal gardens / urban parks with private / domestic gardens). Despite this, a distinguishing factor has been used whereby studies have only been considered where they focus on small greenspaces – reported garden sizes vary from 0.02ha to 0.24ha (where data are available). Table 3 below presents the cooling values for urban gardens that it has been possible to obtain from the sources reviewed. A key finding across the evidence is that cooling effects were evident across the contiguous spaces, despite the small size of the individual patches.

Table 3: Cooling effect values for urban gardens (or small urban greenspaces) extracted from literature reviewed

Type of Urban Green space	Issues / limitations / comments	Cooling effect (°C) - for day time air temp unless otherwise stated	Source
Small gardens (private or communal)			
Garden Teófilo de Braga, Lisbon. Small neighbourhood or communal (rather than domestic) garden. Size 0.24ha. Rectangular garden 95 x 61m in size, surrounded by residential / commercial buildings between 15 and 25m tall with varied shapes, colours and materials	Temperature differential compared between the shaded site inside the garden and the sunny site in an EeW oriented street in the southern part of the studied area. Data collected in 8 different locations along a path during 6 summer days in 2006-2007. Min and max temp were above monthly average on fieldwork days	Median air temperature difference between the values measured in the garden and surrounding streets was 1.6°C and 0.7°C, in sunny or shaded conditions respectively. Max air temperature difference: 6.9°C cooler in garden compared with surrounding areas. Higher differences recorded between shaded and sunny sides of streets which have an approximated EeW orientation than in the NeS oriented streets	Oliveira *et al.* (2011)
Aharon Garden, Tel Aviv, Israel. Small urban garden with trees (0.15ha) (this was the smallest greenspace of 11 sites monitored). Unclear if it is a private or communal garden	Temperature measured in summer August 1996	Daily maximum cooling effect of 4°C compared with average air temperature of surrounding areas at 1500h	Shashua-Bar and Hoffman (2000)
Private courtyard with trees (0.02ha), in Florence, Italy. Unclear if it is a private or communal garden	Temperature differences between urban temperature station and site. Temp measured day and night in Dec-Feb 2001/02 and June-August 2002. Differences between daytime and night time temperature	Park Cool Island effect, in summer, max day time air temperature difference 3°C. Temperature differential expected to be result of reciprocal diurnal shading of walls (courtyard encircled by houses) and tall trees. Even so, this is a notable temperature differential given the small patch size (though this may be in part due to shading by buildings – see row below).	Bacci *et al.* (2003)
Private gardens with trees (0.07ha) in Florence, Italy. Unclear if it is a private or communal garden	Temperature differences between urban temperature station and site. Temp measured day and night in Dec-Feb 2001/02 and June-August 2002. Differences between daytime and night time temperatures	Park Cool Island effect, in summer, max daytime temperature difference approx. 1.5°C	Bacci *et al.* (2003)
Urban gardens around a residential block comprising 5 buildings, in Crete. Vegetation comprising trees, plants and herbs. Seems to be a communal garden site	Theoretical / simulation based using the model 'Envi-Met'. Models 3 scenarios to examine the impact of vegetation in reducing temperature around the block: (a) no vegetation; (b) current state; (c) fruits and vegetables; and (d) aromatic-medicinal	Range of measurements relative to current state. A further more detailed review of the source is required in order to elicit usable temperature differentials	Tsilini *et al.* (2014)

Backyard (grass with trees) compared to 2 streets Munich, Germany 0.16ha	Air temperature measured on hot day in daytime in July 1985	A further more detailed review of the original study would be required in order to elicit useable temperature differentials	Mayer and Höppe (1987) in Bowler *et al.* (2010)
15 urban community gardens in California. Size of gardens not reported	Empirical data. Temperature measured at a height of 1.5-2m above garden bed, every 30 mins, in July to Sep 2016 during drought. Impact on mean and max temperature within garden recorded	Temperature differentials are not explicitly reported in the source. However, regression results indicate cooling factors - tallest vegetation, tree / shrub species richness, grass cover, mulch cover, and landscape level agricultural cover. Warming factors were also reported - garden size, garden age, rock cover, herbaceous species richness, and landscape level urban cover. Trees tend to be located around the edge of gardens but measurements are taken in the centre which may explain why larger gardens have higher temp. than smaller gardens	Lin *et al.* (2018)
Other urban green			
10% increase in urban vegetation, Toronto, Canada	Theoretical / simulation based using the model 'Envi-Met'	Outdoor air temperature reduced by 0.5-0.8ºC in daytime	Wang *et al.* (2016)

2.3. Source of impact (heat effect on health and productivity)

The local climate regulation service focuses on the role urban ecosystems play in modifying temperature and providing an urban cooling effect through evapo-transpiration, shading and lower radiative temperatures as defined by CICES (see section 2.1). The evidence in the second UK Climate Change Risk Assessment (CCC, 2016) included several heat related risks that urban natural capital (via micro climate regulation services) can help mitigate, including:

- **Temperature mortality** - the number of heat-related deaths in the UK are projected to increase by around 250% by the 2050s (median estimate), due to climate change, population growth and ageing, from a current annual baseline of around 2,000 heat-related deaths per year; and

- **Loss of staff hours** - past events suggest extreme outdoor temperatures can have significant effects on productivity, with associated impacts on economic output. The 2003 European heatwave is estimated to have resulted in a reduction in manufacturing output in the UK of £400 to £500 million. Another analysis covering all economic sectors in London alone predicted productivity losses for the 2080s of €1.9bn (2003 prices) (Costa et al., 2016). These empirical events and analyses are underpinned by a robust scientific understanding of the impact of different temperature extremes on productivity at different work rate intensities (ISO 7243).

3. METHODOLOGY

The urban natural capital account for local climate regulation is scoped following a six-step methodology:

- Step 1: Physical account of natural capital extent
- Step 2: Physical account of natural capital condition
- Step 3: Physical account of ecosystem service provision and use
- Step 4: Accounting for the supply and use of ecosystem services
- Step 5: Monetary account of annual provision of ecosystem services
- Step 6: Monetary account of future provision of ecosystem services

This chapter describes this method which has been used to quantify and value the local climate regulating ecosystem service from urban environments in GB, and builds on the methodology original developed for the original scoping study (eftec *et al.*, 2017) by extending it to cover the additional elements discussed in Section 2 of this report. An accompanying Excel document outlines the data sources, assumptions, method steps and calculations that underpin this analysis.

3.1 Physical account of natural capital extent (Step 1)

Urban boundary

The urban boundary used for this analysis was developed by the project team under the UK Urban account scoping project, which is based on the ONS (2011) Built-Up-Area dataset.

The Defra/ONS (2017) principles paper states that the starting point for any classification of ecosystem types is the Land Cover Map (LCM). However, because this is based on land cover, the definition of 'urban' includes gardens, roads and buildings, but excludes most green and blue spaces which are captured under other categorisations (i.e. grassland, freshwaters). Therefore, defining the urban area for the purposes of an urban natural capital account requires a departure from the use of the LCM, with subsequent reconciliation to avoid double counting across UK natural capital accounts by identifying the extent of overlaps with other broad habitat accounts that have been developed using the LCM.

The ONS (2011) Built-Up-Areas dataset was selected for the urban account on the basis that:

(i) it captures all built-up-areas and therefore all areas that will not be included in other broad habitat accounts (this is not the case for Rural Urban Classification 2011 (RUC2011), Major Towns and Cities);

(ii) Other urban classifications (e.g. major towns and cities) can be looked at within this dataset, and

(iii) It is based on physical settlement morphology and not statistical units (i.e. Output Areas that RUC2011 uses) which will extend into rural areas. The basic methodology to 'enhance' the urban boundary involved temporarily applying a variable sized buffer to the existing ONS2011 built up area (BUA) layer. The buffer is scaled in proportion to the area of the polygon (using the equation Buffer width = $0.012 * \sqrt{\text{Polygon area}}$) [11]. This effectively 'captures' the majority of urban green and blue space within each urban area.

[11] We apply a buffer scaled relative to an absolute size rather than relative to the largest polygon (i.e. London) because if the largest polygon expanded and the buffer was expressed relative to this polygon, the size of the buffer applied to other areas would change, even for polygons experiencing no change in size. This could potentially lead to inconsistencies in what is included compared with previous accounts. The scaling results in a buffer of approximately 500m for a polygon the size of Greater London.

The buffer is then collapsed back to the original extent, but including any new 'captured' green and blue infrastructure. For further information on how this boundary was estimated, see the UK Urban NCA scoping study report (eftec et al, 2017).

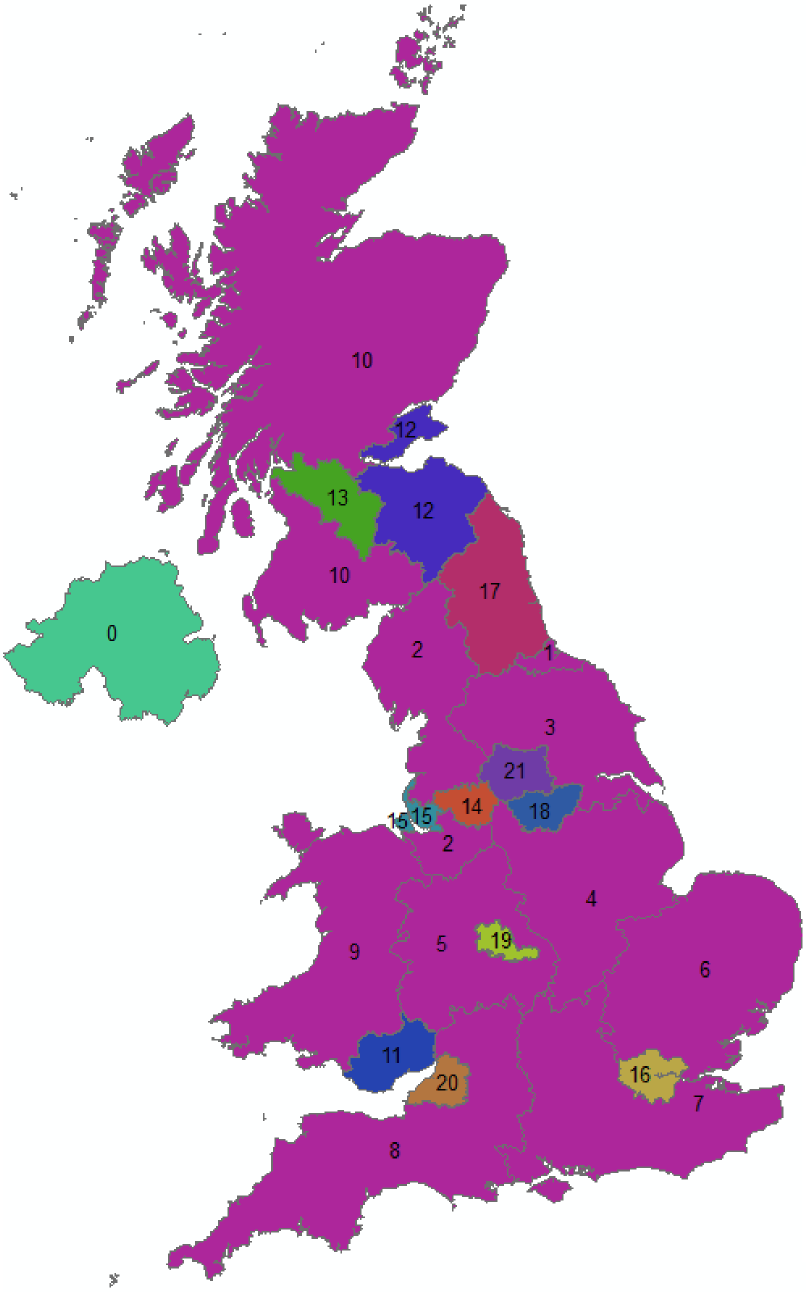
Extent and disaggregated boundaries used in the calculations

The full calculation chain requires knowledge of the spatial extent and boundaries of multiple components: the urban extent, types of natural capital within that extent, administrative boundaries used to differentiate beneficiaries and therefore to calculate economic benefits.

To achieve this, we created a set of regions which comprised the main eleven city regions in GB[12]. Figure 2 shows the combined geometry which shows city regions included in the assessment, and the remaining NUTS1 areas outside those city regions not included in the assessment. Note some city regions encompass large urban conglomerations e.g. Greater Manchester City Region, while others include considerable rural area as well e.g. North East City Region. All spatial calculations were made within these boundaries.

Figure 2: Boundaries of city regions and remaining NUTS1 areas lying outside of those city regions

[12] Note that due to limitations in the data, this study only covers the urban extent of these 11 city regions, not the entirety of urban space in GB.



Key

Code	Region/City region
0	Northern Ireland
1	North East (England)
2	North West (England)
3	Yorkshire and The Humber (England)
4	East Midlands (England)
5	West Midlands (England)
6	East of England (England)
7	South East (England)
8	South West (England)
9	Wales
10	Scotland
11	Cardiff City Region
12	Edinburgh City Region
13	Glasgow City Region
14	Greater Manchester City Region
15	Liverpool City Region
16	London City Region
17	North East City Region
18	Sheffield City Region
19	West Midlands City Region
20	West of England City Region
21	West Yorkshire City Region

The city regions assessed are number 11 through 21.

Physical asset register

The steps below outline the method used to define the total extent of all urban bluespace and greenspace assets[13] in 11 city regions in GB (areas 11 through 21 in Figure 2). This draws on conceptual and empirical findings from the literature review, especially in terms of the (inconclusive) evidence concerning size thresholds (i.e. the minimum width and/or area for linear and polygon features respectively over which a cooling effect can be assumed to occur) and the maximum distance from the edge of blue- or green-space over which a reduced cooling effect can be assumed to occur (i.e. "distance decay" effect).

1) Define the total extent of all bluespace and greenspace within the urban extent, using GIS data:

[13] 'all urban bluespace and greenspace assets' refers to those assets assessed in the original scoping study (eftec *et. al*, 2017) plus the additional assets scoped in to this extension to the original scoping study.

a) **Bluespace features:**

These comprised linear features such as Rivers & Canals, as well as Lakes, Ponds and Reservoirs. 'Natural surface' features in OS MasterMap identified as 'water' were identified. Since cooling effects differ for rivers and canals compared with larger water bodies, these needed to be differentiated in GIS using an automated procedure. This was based on the Polysby-Popper test to determine whether a water body was likely to be a lake or a river, defined by its shape. Where:

Pp = 4*PI*area/perimeter^2

Lakes/ponds and reservoirs were anything with pp > 0.25, while rivers and canals were anything pp < 0.25.

Rivers/canals >25 m wide were identified by buffering them in by 12.5 m. If the resulting geometry had an area of zero then the river must be narrower than 25 m. If greater than zero at least some part was > 25 m. Lakes/ponds/reservoirs <700 m^2 were excluded.

b) **Greenspace features:**
   i) Woodland: This comprised all 'natural surface' features where trees or woodland were mentioned in the recording fields. Woodland < 200 m^2 was excluded and woodland was separated into two size classes (< and > 30,000 m^2). The method is discussed in more detail in the scoping report (eftec *et al*. 2017).
   ii) Grassland: This comprised all 'natural surface' features identified as grassland, which includes areas of open parkland, grassland, playing fields, extensive grass verges etc. Areas < 200 m^2 were excluded. The method is discussed in more detail in the scoping report (eftec et al. 2017).
   iii) Gardens: For this study, gardens were added to the list of natural capital assets to be assessed. Gardens in OS MasterMap are recorded as a 'Mixed Surface'. All areas of Mixed Surface adjacent to buildings were selected, and any contiguous gardens were amalgamated, in order to only include composite areas large enough to provide a service. Only contiguous garden >200m^2 was included for analysis.

c) For all blue and greenspace features, contiguous areas of the same type were amalgamated prior to analysis to avoid problems when calculating and applying buffer zones.

2) Apply size thresholds to select only those features that are large enough to have an assumed cooling effect:
   a) For the purposes of a 'top-down' approach to analysis, an assumption has been made that the cooling effect provided is consistent along the length (linear features) or circumference (other features) of the asset. This assumption is required for the proportional approach adopted to the physical flow account modelling (i.e. calculating the proportion of the urban area comprised of bluespace and greenspace and using this as a factor to adjust the full cooling effect of the bluespace and greenspace, as discussed further in Section 3.3). A more granular, 'bottom-up' approach may also be possible, accounting for variations in urban form / design along the river corridor or adjacent to polygon features (see section 5.2).
   b) ***Apply size threshold to linear features*** by assuming that cooling effects are uniformly attributable to all linear features with a width of ≥25m. In effect: (a) all linear features <25m in width are excluded from the asset register and subsequent physical flow account modelling; and (b) all linear features ≥25m wide are included and treated equally in terms of cooling effect. Based on the literature reviewed (see section 2.2), this size threshold is suitably robust as it is based on empirical evidence that an urban river in the UK measuring 22m wide provided a cooling effect (Hathway and Sharples, 2012); a 25m threshold is applied due to its compatibility with the available GIS resolution. However, this approach may be

conservative as empirical evidence from elsewhere in the world suggest that the cooling effect may increase with increasing river width (see sections 3.8 and 5.2).

c) ***Apply area threshold to other features***. For lakes, ponds and reservoirs, it was assumed that cooling effects are uniformly attributable to all with an area of ≥700m^2, based on the one UK study identified in the literature review (see section 2.2) that examined cooling of urban pools/ponds (using a theoretical / simulation based approach) estimating mean cooling of 0.1°C (O'Malley *et al.*, 2015). This approach is likely to be conservative as empirical and theoretical (simulation based) evidence from elsewhere in the world suggests that cooling effects can arise from smaller waterbodies. For woodlands, grasslands and gardens, the minimum area threshold applied was 200m^2.

3) Apply buffer to blue and greenspace retained after step (2) to identify the area of assumed reduced cooling adjacent to the feature (thereby accounting for the 'distance decay' effect):
   a) For ***linear aquatic features, buffer the waterbody*** to 30m from the edge of the feature (bankside). Within this buffered area, a reduced value for the cooling effect of linear features will be applied uniformly (see Table 4). This approach is likely to be conservative as empirical evidence from the UK suggests: (a) that there is a greater cooling effect 20m from the edge of a river than at 30m; and (b) that a reduced cooling effect can occur up to 60m from edge of the feature (Hathway and Sharples, 2012). The implications of this are discussed further at sections 3.8 and 5.2.
   b) For ***other aquatic features (lakes, ponds, reservoirs), buffer the waterbody*** to 30m from the edge of the feature (bankside). Within this buffered area, a reduced version of the value for the cooling effect of linear features will be applied uniformly. Little evidence was available on the 'distance decay' effect for these features, so the buffer size for linear features was used as a proxy. The implications of this are discussed further at sections 3.8 and 5.2.
   c) For greenspace, the main literature evidence relates to woodland or to wooded parkland. Therefore, we only applied a buffer to woodland, and then only to woodland in the higher size class of >30,000m^2. Buffers were not applied to grassland or gardens due to their primarily small size[14].

3.2 Physical account of natural capital condition (Step 2)

The condition account plays a critical role in representing the role of natural capital in providing benefits, not all of which could be included in the physical or monetary account. The broad dimensions of natural capital condition from the Defra/ONS (2017) principles paper align to the following split:

- **The state of the natural capital asset:** as measured through relevant volume estimates (e.g. timber biomass), biodiversity indicators (e.g. abundance), soil indicators (e.g. carbon content), ecological condition indicators (e.g. water quality) and spatial configuration (e.g. connectivity);

- **Other forms of capital:** as measured through access (e.g. proximity of open access areas to population) and management practices (e.g. agri-environment schemes).

The recording of such information in an account is both data dependent and subject to an understanding of the links between condition (of natural and other capital) and service provision. For this study, some aspects of condition have been incorporated in the account. For example, woodlands, grasslands/parkland and gardens <200m^2 were excluded from the analysis, as were rivers and canals <25m width, and lakes/ponds <700m^2. This recognises that size plays a part in determining

[14] By their nature grassland and gardens are primarily small scale and dispersed throughout the city, therefore it is assumed that buffers are generally not appropriate, and would risk overestimating the total cooling effect.

the level of service provided, and that threshold effects are likely to apply. In addition, woodlands were further subdivided into two categories: <3ha and >3ha. In recognition of the greater service provided by larger woodland patches, cooling within a 100 m width buffer (Bowler *et al.*, 2010) was applied to these areas, as described above.

3.3 Physical account of ecosystem service provision and use (Step 3)

Physical flow account

The steps below outline the method used to estimate the physical flow of local climate regulation services (i.e. a cooling effect T_{urban} – $T_{blue/green}$ in ºC) for the urban bluespace and greenspace assets defined in the physical asset register (see section 3.1).

1) Sum the area of the bluespace and greenspace assets assessed (this is the area where a cooling effect is assumed to occur). Sum the values for the area of the buffer around the assets assessed, where relevant (this is the area where a reduced cooling effect is assumed to occur).

2) Calculate the percentage of urban extent comprised of bluespace and greenspace assets and for the total area of the buffer around each of these asset classes, where a buffer is applied[15].

3) Calculate the proportional impact on city-level temperatures[16] caused by the urban cooling effect of bluespace and greenspace features and their buffers (‘distance decay’ effect) using the cooling values (T_{urban} – T_{blue} in ºC) set out in Table 4 below. The cooling values used (Table 4) have been obtained from the evidence review summarised in section 2.2 above. The criteria for selecting values, where possible, was to obtain them from sources relating to studies: (i) undertaken in a UK context; and (ii) that were empirical in nature (rather than based on models / projections) – i.e. they involved field measurements of cooling effects in different contexts / settings.

Table 4: Width of buffers and temperature differentials applied for urban blue and greenspace

Asset	Width of buffer to apply (m)	Temperature differential (deg C)	
		Green/blue infrastructure	Buffer
Urban blue space			
Rivers, canals (>25m wide) [17]	30	-1.4	-0.8
Lakes, ponds, reservoirs (>700m²)[18]	30	-0.1	-0.057

[15] Note that where zones overlap we assume the temperature change is additive, and so total effect is calculated cumulatively. In the absence of empirical measurements on this, it is a realistic assumption.

[16] While not directly reflective of the cooling effect in reality, this approach is thought a reasonable approximation and adopted for the purpose of valuation, as the impact on GVA is a calculated average impact across the city region.

[17] Cooling effect values for linear urban bluespace features have been drawn from Hathway and Sharples (2012), which is an empirical study from the UK (River Don, Sheffield). Where multiple values are available in the study, average cooling values (mean) have been used as follows: (a) seasonal average (May and June) cooling values – average calculated for the feature itself and the buffer; and (b) average cooling values for different buffer increments (river edge / 0m, 20m and 30m from the river edge) – average calculated for the buffer only.

[18] Cooling effect values for polygon urban bluespace features have been drawn from O’Malley *et al.* (2015), which is a theoretical (simulation based) study from the UK (Seagrave, London). This study did not include an explicit assessment of cooling in the buffer zone (‘distance decay’) so the cooling value here has been adjusted down in line with the feature to buffer cooling effect ratio for linear features adapted from Hathway and Sharples (2012) (i.e. whereby the cooling effect in the buffer is 57% of the cooling effect for the area encompassed by the feature itself).

Urban green space			
Woodland (200 < x <30,000m^2)	0	-3.5	n/a[19]
Woodland (>30,000m^2)	100	-3.5	-0.52
Open parks & grassland (>200m^2)	0	-0.95	n/a
Contiguous gardens (>200m^2)	0	-0.95	n/a

***Worked example:** for an urban area comprised of 10% 'rivers', the cooling effect of these is assumed to be 10% of the full cooling value of rivers (i.e. 10% of -1.4°C or -0.14°C).*

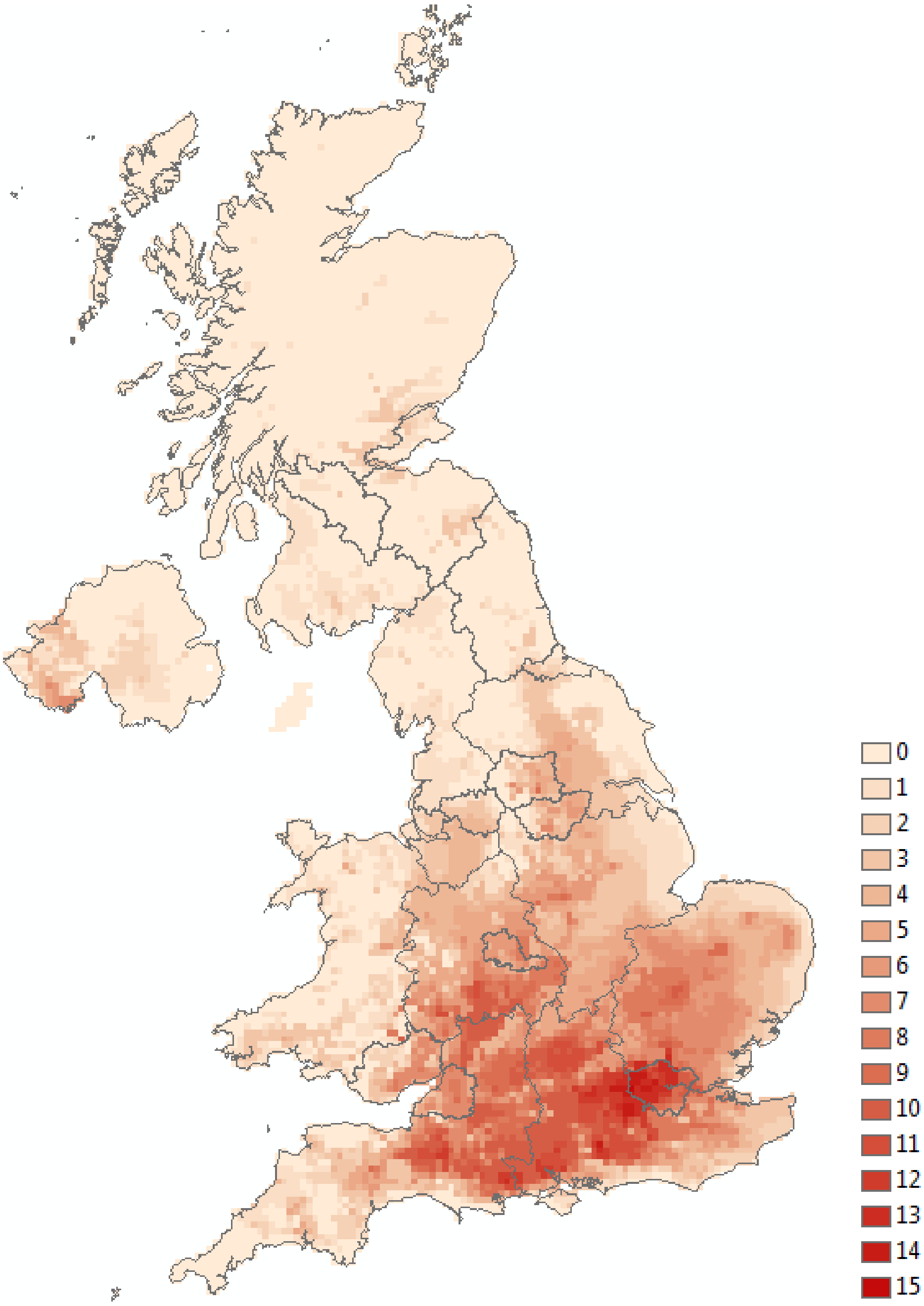
Calculation of cooling effect was applied to temperature maps for GB to provide greater spatial resolution of the physical flow account. Temperature data was taken from the Climate Hydrology and Ecology research Support System meteorology [CHESS-met] dataset (1961-2015) which provides daily meteorological variables on a 1km grid over GB (Robinson et al., 2017). It is primarily derived from the Met Office Rainfall and Evaporation Calculation System (MORECS) dataset (Hough and Jones, 1997), and downscaled to 1km resolution taking into account local topographic information (Robinson et al., 2016). For each 1 km gridcell, the number of days that the daily maximum temperature fell within the following temperature bands were calculated, and for each year from 2007 – 2016 (in degrees Celsius):

- 28-29
- 29-30
- 30-31
- 31-32
- 32-33
- 33-34
- >34

An example of the spatial distribution for hot days >28°C for one of the hotter years within the specified time period (2013) is shown in Figure 3. The weighted average of number of days within each band was calculated for each of the geographic regions shown in Section 0.

Figure 3. Number of days where daily maximum air temperature lies above 28oC, in 2013.

[19] No buffer is applied to small scale Woodland due to uncertainty around the threshold at which impacts would be felt, this is likely a conservative assumption.



4) Sum the city-level proportional urban cooling effect for urban bluespace and greenspace, from step (3) above (i.e. create an area-weighted average of the temperature differential to be applied across the urban extent, within each city region (see Figure 2)), and calculate what temperatures would be if this bluespace and greenspace was not present (see section 3.5). The assumption, is that temperatures (e.g. seasonal averages, extreme events) would be this much warmer without the cooling effects provided by the extant urban natural capital assets.

   Worked example: *for an urban area comprising 10% 'rivers' and 2% 'river buffers', the cooling effect of each category would be: (a) urban rivers -0.14°C (i.e. 10% of -1.4°C); and (b) urban rivers buffer -0.016°C (i.e. 2% of -0.8°C). Therefore, the total cooling of urban rivers is assumed to be: -0.156°C.*

3.4 Accounting for the supply and use of ecosystem services (Step 4)

Accounting for ownership and management of the ecosystems which supply the services (defined in the Defra/ONS (2017) principles paper as enterprises, households, governments, rest of the world) would require mapping ownership of the natural capital that are providing the service which is outside the scope of this study. Instead, we focus on beneficiaries of the cooling effect provided by urban natural capital. We make the assumption that only certain sectors are affected by excessive temperatures, and that these are found predominantly within the urban extent developed in the scoping study. Without knowing precise locations of each activity, we make the assumption that these have the potential to occur anywhere within the urban extent, and thus potential service use is distributed uniformly across the urban extent.

3.5 Monetary account of annual provision of ecosystem services (Step 5)

The monetary account assessment is focussed on avoided labour productivity loss and avoided air conditioning costs.

Avoided labour productivity loss

The monetary account captures the economic value (£) of the benefits derived from the physical flows of local climate regulation ecosystem services that have been quantified in the physical flow account. In the methodology used, the benefits valued are the productivity losses[20] avoided during hot weather events as a result of the cooling effect of the extant natural capital (see evidence from empirical studies in Table 2 and Table 3). For commensurability with other national accounting data, this should be the 'exchange value' observed in markets or 'imputed exchange value' (i.e. indirectly measured or estimated) where markets do not exist.

1) Calculate the city-level / aggregated cooling effect of urban natural capital as per the physical account method (see section 3.3).

2) Determine GVA/day of each sector (ONS Regional firm-level productivity analysis for the non-financial economy).

3) Use productivity loss functions from Costa *et al.* (2016) to identify productivity loss estimates (% less than "full work") for each sector (work intensity) affected under the different hot day temperature bands being used for the city being assessed[21]. See Table 5 for productivity factor for each temperature band (expressed from 1.00 for 100% productive to 0.00 for 0% productive), for each sector.

4) Determine productivity loss for each sector without vegetation. Productivity losses without vegetation are calculated as a proportional increase towards the productivity losses at the next temperature band, based on the temperature change of the combined cooling effect of each city-region.

[20] Occupational heat exposure guidelines (such as ISO7243) state maximum heat exposures in jobs / sectors of economic activity at different levels of work intensity measured in Watts (Kjellstrom et al., 2009). Table A.5 in the Costa et al. (2016) online appendix maps work intensity categories from ISO 7243 to different sectors of the economy. Following the approach adopted in the scoping study, this categorisation is used to identify work intensity and productivity loss functions for UK urban economy sectors as part of this aspect of the urban heat account.

[21] Depending on the magnitude of the "hot day" temperatures for a given city, some, all or none of the work intensities may be affected – the higher the "hot day" temperature, the more work intensities / sectors that will be affected.

5) Determine productivity loss averted at each temperature band due to urban vegetation. Subtract productivity loss without urban cooling effect (3) by productivity loss with urban cooling effect (4).

6) Determine the hot days at each temperature band for each city region (Met office data).

7) Determine total productive days lost due to hot days, by sector. For each sector, sum the multiple of productivity loss averted per temperature band by the number of hot days at each temperature band.

8) Calculate GVA loss averted. For each sector, multiply GVA per day (2) by productive days lost due to hot days (7) and sum values.

9) Apply a factor for averted losses due to adaptation measures. Evidence from Costa et al (2016) suggests that averted losses from (i) air conditioning (in London) can be ≤85% (ii) behavioural change (in London) can be ≤40%.

   Unfortunately, there is no estimate for the combined impact of behavioural change and air conditioning. Additionally, the averted loss from air conditioning and behaviour change would vary by sector. In general, it is thought that where air conditioning exists the scope for behaviour change would be reduced (e.g. office and retail works), and where air conditioning doesn't exist the scope for behaviour change would be greater (e.g. construction workers and mining and utilities). As such, for the purposes of this analysis, a 40% reduction is applied to more labour intensive or non-office based sectors for averted losses due to behaviour change (Mining and Utilities; Manufacturing; Construction; Wholesale and Retail trade; repair of automobiles; Transportation and storage; Accommodation and food service activities), and a 85% reduction is applied for less labour intensive or office based sectors for averted losses due to air conditioning (Information and Communication; Real Estate Activities; Professional, scientific and technical activities; Administrative and Support Service; Other Services).

   It should also be noted that the valuation results are dependent on the size of the effect being mitigated (i.e. hot days), which is subject to fluctuate year on year. This iteration of the accounts is based on a five year average number of hot days in each temperature band, between 2012 and 2016.

Table 5: Productivity at each temperature band, for each sector

Sector	Most relevant sector in Costa *et al.* (2016)	Average work intensity in Watts (Costa *et al.*, 2016)	Work intensity category (Costa *et al.*, 2016)	Worker productivity at different hot day temperature bands - Low						
Temperature				**28.0 - 28.9**	**29.0 - 29.9**	**30.0 - 30.9**	**31.0 - 31.9**	**32.0 - 32.9**	**33.0 - 33.9**	**33.0 - 34.9**
Mining and utilities	Other industry	295	Moderate (3)	1.00	0.85	0.60	0.42	0.20	0.00	0.00
Manufacturing	Manufacturing	240	Light / moderate (2)	1.00	1.00	0.95	0.60	0.30	0.00	0.00
Construction	Construction	355	Moderate / high (4)	0.90	0.70	0.55	0.35	0.15	0.00	0.00
Wholesale and retail trade; repair of motor vehicles	Wholesale and retail trade	240	Light / moderate (2)	1.00	1.00	0.95	0.60	0.30	0.00	0.00
Transportation and storage	Manufacturing	240	Light / moderate (2)	1.00	1.00	0.95	0.60	0.30	0.00	0.00
Accommodation and food service activities	Manufacturing	240	Light / moderate (2)	1.00	1.00	0.95	0.60	0.30	0.00	0.00
Information and communication	Information and communication	180	Light (1)	1.00	1.00	1.00	1.00	0.55	0.00	0.00
Real estate activities	Financial and insurance activities	180	Light (1)	1.00	1.00	1.00	1.00	0.55	0.00	0.00
Professional, scientific and technical activities	Financial and insurance activities	180	Light (1)	1.00	1.00	1.00	1.00	0.55	0.00	0.00
Administrative and support service activities	Public adminsitration and defence	240	Light / moderate (2)	1.00	1.00	0.95	0.60	0.30	0.00	0.00

Air conditioning savings

The value for avoided air conditioning costs is based on the approach developed in the scoping report amended to be applicable to the individual city regions. The London assessment in Rogers *et al* (2015) identifies how the cooling effect of urban vegetation in terms of air conditioning costs avoided results in an annual benefit of £4,139,159 per year (for Greater London)[22], based on an assessment of the cooling effect of urban vegetation on building energy use (including air conditioning costs). This study applies a model parameterised for the US housing stock, and includes all street trees including effects for shading and evapotranspiration. As such it is not perfectly suited for adaptation to this study, but is thought to be the best estimate available.

As similar data is not available for each city region, air conditioning cost savings are estimated based on a proportion of this value (uplifted to 2017 prices) relative to an estimate of the air conditioned floor space in each city region compared to the air conditioned floor space in London. The estimate of air conditioned floor space is derived from Abela *et. al* (2016) to find the total air conditioned floor space (as estimated for 2012) for each region relative to London. The regions do not align exactly with the city regions assessed in the study, and so where multiple city regions were located within one region, the proportion was split amongst them. As well, the approach implicitly assumes that the other city regions have the same proportional service to that provided by London's vegetation. While there is limitations to the approach, it is still thought to provide a reasonable estimation based on the existing data.

3.6 Monetary account of future provision of ecosystem services (Step 6)

This account values the urban natural capital asset(s) based on the present value of the stream of (annual) ecosystem services that the asset(s) will provide over a future period of time. The Defra/ONS principles paper states that a 100-year asset life should be used to reflect the longevity of renewable natural assets. In principle, the asset value estimate should account for expected variations in both the physical and monetary flow of ecosystem services over the 100-year period. In practice, forecasting future flows of benefits and market prices/values is subject to significant uncertainty. For the purpose of this scoping study, the following assumptions are used:

1. A constant physical flow assumption is made for all ecosystem services (i.e. the amount of ecosystem services produced remains the same over the 100 years), except for a projection of the number of days at elevated temperatures in 2080 estimated using UKCP09 projections and an assumed linear progression between the current value of avoided productivity losses in 2016 and the value in the future in 2080 (estimated for each city-region based on an uplift in the degree of their hot days[23]). The estimated avoided energy cost associated with air conditioning is assumed to remain the same for the purposes of this assessment (although in reality this could be expected to increase with the elevated temperatures projected under a changing climate such as UKCP09).

[22] The model that the referenced study is based on was parameterised for the US housing stock and so may not be fit for purpose for the London building stock. As no better value was found this value is adopted for the purposes of this study, but is a limitation which future research should seek to address.

[23] The UKCP09 indicator "projected changes to the warmest day of summer" suggests that for a 50% probability level (central estimate) under a medium emissions scenario in 2080, warm days for the southern half of the UK are likely to be 2-4oC hotter and for the northern half of the UK, warm days are 4-6oC hotter (Murphy et al., 2009). For city regions in the southern half of the UK a 2oC increase is assumed, while for city regions in the northern half of the UK, a 4oC increase is assumed. Note that this projection is for the increase in temperature of hot days, rather than for the increase in the number of hot days, the data is adjusted accordingly in the accounts.

2. A annual uplift is applied to the monetary values to account for year on year increase in GVA over the 100 year assessment period. For the first 30 years this uplift is 2% annually, decreasing to 1.5% for years 31 – 75, and 1% for years 76 - 100[24].

3. For discounting the future flows of ecosystem service values Green Book guidance for project appraisal (HM Treasury, 2011) will be applied in line with Defra/ONS (2017). This starts with a 3.5% discount rate for the first 30 years, 3.0% for years 31 – 75 and 2.5% for years 76 – 100.

3.7 Caveats and Limitations

There are several limitations and caveats inherent to the accounting approach to the local climate regulation extensions described in the sub-sections above. An overview of these is provided at Table 6. There may be scope to address some of these limitations through further research and future iterations of the local climate regulation account (e.g. additional literature review and / or empirical research to understand the 'distance decay' cooling effect of bluespace and greenspace features). Recommendations for this are outlined in section 5.2. Key limitations and caveats to the approach are described in further detail in the text below Table 6.

Table 6: Overview of caveats and limitations inherent to the accounting approach

Key to impact of caveat / limitation on valuation estimates

↑ overestimate	↓ underestimate	? Uncertain impact

Caveat / limitation	Impact on valuation estimates	Comments
Cooling effect estimates may be conservative	↓	Simplistic approach to physical account modelling means that the cooling effect of bluespace features is likely to be underestimated.
Use of an area weighted average temperature differential / assumptions concerning location of beneficiaries	?	Simplistic approach to physical account modelling means that cooling effect values are relatively crude. Also, the approach doesn't account for locally felt cooling effects (e.g. shading by street trees) and impacts on local beneficiaries.
Cooling effect values for linear bluespace feature buffer zones are simplistic and conservative	↓	Use of a uniform cooling value for linear bluespace feature buffer zones is likely to result in an underestimate of cooling in these areas.
No robust evidence on buffer zone cooling effect for polygon bluespace features and greenspace features	↓	Lack of clear evidence for buffer zone cooling for these features. Empirical values for linear bluespace features were used as a proxy though some theoretical literature suggests that cooling for polygon bluespace features (lakes, ponds etc) and greenspace is likely to be higher.
Elements of total urban bluespace and greenspace have not been valued	↓	The value of the asset may be underestimated as some features are absent from the physical asset accounting (e.g. street trees).
The assumption of consistent cooling along a linear	?	Channel characteristics (depth, width etc) are variable and likely to result in different cooling

[24] Uplift values as pers.comm. Colin Smith, 2018.

Key to impact of caveat / limitation on valuation estimates

↑ overestimate	↓ underestimate	? Uncertain impact

Caveat / limitation	Impact on valuation estimates	Comments
bluespace feature is a simplification		effects. This level of detail was not covered in the physical account modelling.
Lack of specific cooling effect values for some assets	?	Use of proxy values in some instances and / or values obtained through simulations (modelling) rather than empirical measurement.
Urban form adjacent to features not considered	?	The effect of urban form adjacent to natural capital features on cooling within the buffer zone was not considered in the modelling.
Limited consideration of seasonality	↓/↑	Cooling effect of bluespace features may vary with season (i.e. temperature and flow). This was only partially addressed in the modelling.
Day / night time variation in cooling effect	↑	Cooling effect of bluespace features is more pronounced during the day and may actually contribute to warming during evening. Night time warming was not addressed.
Canals and reservoirs are a mix of natural / built capital	↑	These assets co-produce cooling therefore a portion of the benefit will be attributable to built capital.
Limit of cooling effect from urban vegetation during droughts	↓	As a portion of the cooling effect is due to evaporative cooling, and under severe drought conditions plants may shut down their photosynthesis, and resulting transpiration, this element of cooling may be lost.
Level of avoided air conditioning	?	Avoided cost of air conditioning relies on a value for London based on modelling of the US housing stock which may not be a true reflection of the London housing stock. Proportional value added to each city region is based on an extrapolated estimate of air conditioned floor space that could be updated with better evidence.
Future impact of climate change	?	The assessment of future climate impact relies on broad estimation of the number and degree of hot days in the future across GB.

- ***Cooling effect estimates may be conservative***. The simplistic approach to the physical account modelling means that: (a) it is assumed all linear features ≥25m width have the same cooling effect. While this is consistent with the best available evidence from the UK (Hathway and Sharples, 20102), evidence from elsewhere in the world suggests that the cooling effect of linear features increases with increasing width; (b) those linear features <25m have no cooling effect for modelling purposes due to resolution limitations in the available GIS; and, (c) a cooling effect is assumed from other features (lakes / ponds / reservoirs) only where they are ≥700m^2 in area. While this is consistent with the best available (albeit simulation based) evidence from the UK (O'Malley *et al.*, 2015), evidence from elsewhere in the world suggests that smaller polygon features can give rise to cooling effects also (see Table 2).

- ***An area-weighted average temperature differential over the areas lying within the urban extent***, as applied in the scoping study, is used as the basis for calculating the cooling effect. In principle, the calculation of impact on beneficiaries would also be spatially explicit at fine scale, (i.e. to relate actual location of activities to actual locations where temperature cooling happens). In practice, this is likely to be very difficult as data would be needed on exactly where all activities are occurring across the whole UK. While there is some 'transport' or diffusion of the cooling effect in the atmosphere, this will also lead to dilution of the cooling effect, meaning that this change in temperature will affect temperatures in nearby areas to a lesser extent. Coupled with this, the combination of urban natural capital and buffer zones means that a substantial part of the urban environment is mitigated to some extent, and for the purpose of modelling, due to a lack of data to model more granularly, the cooling effects are assumed to be uniformly distributed. The biggest limitation is currently location of beneficiaries, hence the necessary simplification of the area-weighted cooling that has been applied and the necessary assumption that beneficiaries are distributed uniformly across the urban area.
- ***Cooling effect values for linear feature buffer zones are simplistic and conservative***. The best evidence available in the UK suggests the existence of a 'distance decay' type phenomenon for the cooling effect of linear features (notably rivers) in a buffer zone adjacent to the feature (Hathway and Sharples, 2012). Cooling is variable as distance from the edge of the feature increases. Generally, cooling decreases with increasing distance, with cooling greatest over the river, steadily declining up to approx. 30m from the river edge in the UK study (ibid)[25]. While reduced differential values are reported in the UK study at different distance bands up to 30m from the river edge, this level of detail was beyond the scope of the physical account modelling, instead, using the Hathway and Sharples' (2012) mean average cooling values for May and June at different distances from the river, an average value was used to take account of the distance decay up to 30m from the river edge and applied as a uniform cooling value for the entire 30m buffer. Using the average value for the buffer helps to take into account the distance decay, however the physical account modelling of flows of local climate regulation services in the buffer zone of linear features is likely to be underestimated particularly where the actual cooling extends beyond 30m.
- ***No robust evidence on 'distance decay' effect for other bluespace and greenspace features***. Within the scope of the review undertaken it was not possible to ascertain any robust evidence concerning a cooling effect of aquatic features (lakes / ponds / reservoirs) or greenspace features such as grassland and gardens in the area adjacent to the feature (i.e. a 'distance decay' effect in the buffer zone). As a proxy therefore, empirical cooling effect values for linear feature buffer zones were used for other bluespace features, as explained above (Hathway and Sharples, 2012). However, conceptual evidence concerning the factors that contribute to cooling from urban natural capital features, including within adjacent buffer zones, suggests that cooling within the buffer zone of polygon features may actually be more pronounced and extend further than that for linear features (e.g. due to the size and volume / thermal mass of the waterbody and the increased wind related cooling or turbulence on the leeward side of features). This nuance has not been addressed in the physical account modelling.
- ***There may be elements of total urban bluespace and greenspace which are not valued***. Beyond those elements excluded on the basis of size (area / width) thresholds, some features may be excluded from the asset register due to method and data issues (i.e. the way in which the features are delineated spatially). This means that the value of the asset (productivity losses avoided in £) may be underestimated as some features are absent from the physical asset accounting. A case in point is street trees which have not be considered in any of the accounts although they provide important cooling effects, especially locally due to shading. This particular

[25] Although Hathway and Sharples (ibid) also report an unexplained phenomenon at 60m whereby the cooling effect actually increased in the June measurement, though as this was unexplained this value was not included in the current analysis.

service is assessed within the US Forestry Service i-Tree Eco[26] software package (as 'energy effects') and there may, therefore, be a case for using i-Tree in future iterations of the account (see section 5.2).

- ***The assumption of consistent cooling along the length of a linear feature is a simplification***. This is because river characteristics (e.g. channel width, depth) will most likely vary along the length of the watercourse, which may affect cooling potential (e.g. cooling mechanisms linked to the volume / mass of water available, and rate of water flow). However, this level of detail for the physical account analysis was beyond the scope of the current study. Additionally, it is possible that where cities are close together there may be a downstream effect of transported UHI, though we lack evidence to substantiate this potential cumulative effect.
- ***Lack of specific data on cooling values for some urban bluespace and greenspace assets***. The preference within the physical account modelling was to use cooling effect values (T_{urban} - $T_{blue/green}$ in ºC) obtained from empirical, UK based studies that assess the specific feature of interest (e.g. rivers, canals, lakes). This 'gold standard' approach was only possible for urban rivers (Hathway and Sharples, 2012). UK specific values were available for other bluespace features though the source used was the simulation based (theoretical) study from O'Malley *et al*. (2015) and it was not clear exactly the nature of the polygon features that were being assessed in the modelling (e.g. they may have a built capital component as SuDS infrastructure and the assumed 700m^2 threshold value may relate to the combined area of several smaller features). No specific cooling effect values data was available for canals (which have a more static flow regime than rivers and therefore potentially less of a cooling effect), reservoirs and the buffer area (i.e. the cooling effect 'distance decay' zone) for non-linear bluespace features. These limitations will impact the accuracy of the physical flow account modelling undertaken.
- ***The effect of urban form / design in the river corridor and adjacent to other bluespace features***. The current approach does not seek to incorporate the influence of urban form / design on the magnitude or extent of cooling provided by urban bluespace features, including in the buffer / distance decay zone. Empirical evidence from the UK (River Don, Sheffield) shows clearly that urban form / design does influence the cooling effect of urban rivers (Hathway and Sharples, 2012). A bottom-up approach to estimating physical flows of local climate regulation services is outlined at section 5.2, to better account for this phenomenon via a more granular analysis of different categories of urban form / design in the river corridor and the impact of this on cooling (this was beyond the scope of the current study).
- ***The current approach seeks to incorporate seasonality of temperature differentials but is limited***. This is a critical issue as there is some evidence to suggest that cooling increases with increasing temperature but also that these functions start to diminish later in the summer, for example due to warmer water temperatures, lower flows etc (see for example Hathway and Sharples 2012; Theeuwes *et al.*, 2013). This was addressed as far as possible by selecting values from Hathway and Sharples (2012) based on data for two hot periods in May and June, and averaging these to take into account that cooling was lower in June than May. However, it is anticipated that cooling may diminish further later in the summer (e.g. August) when most "hot day" events are likely to occur and therefore when demand for the cooling effect of urban bluespace features is likely to be highest - hence the cooling may be overestimated for these periods. Detailed assessment of this seasonality effect within the physical flow account modelling was beyond the scope of the current study and should therefore be an important consideration for future work.
- ***Day time / night time variation in the cooling effect of urban bluespace and greenspace***. The cooling effect provided by urban bluespace is typically more pronounced during the day. Studies have also found that urban waterbodies can actually contribute to warming in the evening during later summer (due to increased surface water temperature). The focus of the current valuation approach (monetary account – see section 3.6) is on day time productivity losses, so

[26] https://www.itreetools.org/eco/overview.php

this limitation is likely to have a more limited impact on the resulting estimates. However, future work should consider the extent to which evening warming related to urban bluespace has been evidenced and how this may be usefully factored into consideration of urban local climate regulation (in particular if different valuation methods were applied – e.g. seeking to value reduced morbidity / mortality). Future work could also further consider the day time /night time variation in cooling effect of greenspace as there is some uncertainty in the literature of the degree of impact from greenspace at different times of day.

- ***Canals and reservoirs are a mix of natural and built capital***. This means there is a co-production element to the cooling effect of these urban bluespace features, caused by the combined effect of built and natural capital. In consequence, the value of these assets may be overestimated as a portion of the benefit that will be attributable to built rather than natural capital, though the degree of this attribution is arguable.
- ***Implications for the capacity of urban vegetation to provide a cooling effect in times of drought***. As a portion of the cooling effect is due to evaporative cooling, and under severe drought conditions plants may shut down their photosynthesis, and resulting transpiration, this element of cooling may be lost[27]. This would not happen immediately in dry conditions, and varies by plant type. For example, where grassland dies off, the effect will be lost until new grass has regrown, for trees, there will still be a degree of cooling effect from shading, and photosynthesis may resume quicker once reintroduced to water. This situation would arise from extended dry periods rather than a limited number of hot days. It may be able to model this in theory but would require an involved process as the model would need to calculate the soil moisture deficit from daily meteorological data, coupled with information on soil types, supplementary water sources (i.e. watering, drainage and sewerage networks, etc.), and other contributing factors.
- ***Air conditioning costs are estimated proportionally to each city region based on the quantity of air conditioned floor space present compared to London, relative to the air conditioning cost savings found for London***. This approach provides a reasonable approximation but does not consider variation in the demand for air conditioning across the city regions, air conditioning use below the hot day threshold which may result in additional cost savings, nor additional costs associated with carbon and other externalities of energy production for air conditioning. Additionally, the source cited for the air conditioning cost savings for London uses a model which is parameterised for the US housing stock, which may not be a good fit for London, or elsewhere in the UK. Furthermore, the referenced study includes all street trees and so has a different natural capital asset base and includes effects of both shading and evapotranspiration, and the approach to applying a value to other city regions assumes vegetation in other city regions has same proportionate service to London vegetation.
- ***Future impact of climate change***. The approach to the future impact of climate change applies a broad estimate of the increase in the number of hot days and the degree by which they will increase in temperature across GB by 2080. The approach does not account for specific regional variations in either number or degree of hot days. There is room for the refinement of this approach based on more robust estimates of the impacts of future climate change in terms of hot days in each city-region.

[27] The effect of drought on the cooling capacity of urban grassland in Greater Manchester has been explored in Gill et. Al (2013).

4 RESULTS

This section describes the outputs from this study including the physical account of natural capital extent, condition and ecosystem service provision, and the monetary accounts estimating annual values and asset values. An accompanying Excel document (Annex 1) provides details on the data sources, assumptions, method steps and calculations that underpin this analysis. Note that results are for GB only and extent results will differ slightly from the scoping account, due to mis-matches in administrative boundaries of different datasets. This is generally relatively minor (<1% of area).

4.1 Physical account of natural capital extent and condition

Table 7 shows the extent of urban greenspace and blue space across the 11 city regions within GB. It acts as an asset register indicating the presence of natural capital. The predominant assets are Park and grassland, and Gardens. Bluespace makes up a relatively small component of the urban ecosystems.

Table 7: Extent of greenspace and bluespace in GB's city regions (millions of hectares)[28]

Asset	Area	Proportion of total urban area
Woodland	417	6%
Park/grass	1,612	24%
Gardens[29]	1,746	26%
River/Canals	35	<1%
Lakes/Ponds	26	<1%

4.2 Physical account of natural capital condition

Accounting for the condition of natural capital assets in a study of this scale is inherently difficult and resource intensive. As an initial indication, environmental assets were mapped according to size, to account for thresholds which would provide a greater degree of benefit. Buffer zones were also measured to account for distance decay of the benefits provided. Table 8 shows the area of environmental assets disaggregated to account for condition.

Table 8: Greenspace and bluespace by size and buffer area (millions of hectares)

Asset	Area
Woodland <3ha	295
Woodland >3ha	121
Woodland buffer	324
Parks/grass >200m2	1,612
Gardens >200m2	1,746
Rivers/Canals >25m	35
Rivers/Canals buffer	45
Lakes/Ponds >700m2	26
Lakes/Ponds buffer	37
Total possible urban area	6,627

[28] Excluding areas below the minimum assessed size threshold.
[29] Includes all gardens, defined in OS Master Map as 'mixed surfaces'

4.3 Physical account of ecosystem service provision

The physical account measures the cooling benefit provided by the environmental asset. Table 9 shows the cooling effect in each of the 11 city regions in aggregate, and broken down by greenspace and bluespace ecosystems. The combined cooling effect is relatively stable across city regions, between 0.63 degrees Celsius, and 0.88 degrees Celsius. For all city regions, greenspace provides greater overall cooling than bluespace, however the relative contribution of woodland, parks and grassland, and gardens varies between them.

Table 9: Total cooling effect of greenspace and bluespace in each of GB's city regions (degrees Celsius)

	Cardiff City Region	Edinburgh City Region	Glasgow City Region	Greater Manchester City Region	Liverpool City Region	London City Region	North East City Region	Sheffield City Region	West Midlands City Region	West of England City Region	West Yorkshire City Region
Total effect	-0.71	-0.88	-0.80	-0.75	-0.63	-0.72	-0.65	-0.73	-0.72	-0.69	-0.83
Woodland	-0.23	-0.39	-0.32	-0.24	-0.15	-0.25	-0.17	-0.23	-0.21	-0.19	-0.28
Parks/grass	-0.20	-0.24	-0.22	-0.27	-0.19	-0.21	-0.22	-0.20	-0.21	-0.19	-0.32
Gardens	-0.26	-0.24	-0.24	-0.22	-0.28	-0.24	-0.25	-0.29	-0.28	-0.29	-0.22
Rivers/canal	-0.01	-0.01	-0.02	-0.01	-0.01	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01
Lakes/ponds	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The value of the heat mitigation service is strongly governed by the number of hot days and its spatial pattern across the UK, with value rising non-linearly with temperature due to more sectors being affected at increased temperatures. Table 10 shows variation in hot days > 28 deg C in the city regions. The most recent year for which data is available, 2016, was the second hottest year of the period 2007-2016, with the hottest being 2013 with almost double the average number of hot days compared with 2016. Note the spatial pattern varies over time. London was consistently the hottest city region, while next hottest varies (e.g. shifting from Sheffield to West Midlands to West of England).

Table 10: Number of hot days in each temperature band for each city region, from 2007 to 2017

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Cardiff City Region	0.00	0.29	0.46	0.00	0.00	0.06	3.50	0.20	0.61	1.28
Edinburgh City Region	0.00	0.00	0.28	0.00	0.00	0.00	0.42	0.00	0.04	0.21
Glasgow City Region	0.00	0.00	0.21	0.00	0.00	0.00	0.10	0.16	0.00	0.24
Greater Manchester City Region	0.00	0.00	1.28	0.00	0.26	0.00	2.63	0.00	1.63	0.98

Liverpool City Region	0.00	0.03	1.97	0.00	0.00	0.00	2.03	0.84	1.94	1.00
London City Region	0.88	1.88	5.27	5.97	5.83	5.05	11.59	4.25	2.95	8.20
North East City Region	0.00	0.00	0.02	0.00	0.00	0.00	0.20	0.01	0.31	0.35
Sheffield City Region	0.21	0.08	0.89	0.32	3.08	0.37	3.56	0.60	1.65	2.42
West Midlands City Region	0.08	0.00	1.75	0.00	1.39	0.11	5.81	0.31	2.25	2.81
West of England City Region	0.00	0.36	1.47	0.00	0.00	0.28	6.32	0.42	1.70	1.62
West Yorkshire City Region	0.00	0.02	0.69	0.01	1.52	0.01	2.42	0.36	1.14	1.10
Overall average by region	0.11	0.24	1.30	0.57	1.10	0.53	3.51	0.65	1.29	1.84

As the model is focused on investigating the avoided impact of hot days, clearly the number of hot days in a given year plays a big factor in the overall value of the natural capital asset on any given year. This study assesses the value based on a five year average number of hot days in each temperature band, between 2012 and 2016. Hot days in each temperature band are displayed for each city region in Table 11. For the most recent year, 2016, the number of hot days were above average. For example, the London City Region experienced 8.20 hot days compared to a five-year average of 6.41 days.

Table 11: Days in temperature bands for each city region, five year average

	Cardiff City Region	Edinburgh City Region	Glasgow City Region	Greater Manchester City Region	Liverpool City Region	London City Region	North East City Region	Sheffield City Region	West Midlands City Region	West of England City Region	West Yorkshire City Region
Combined	1.13	0.13	0.10	1.05	1.16	6.41	0.17	1.72	2.26	2.07	1.00
28.0 - 28.9	0.7	0.1	0.1	0.5	0.6	2.2	0.1	1	1.2	1	0.5
29.0 - 29.9	0.3	0	0	0.2	0.3	1.6	0	0.2	0.4	0.6	0.2
30.0 - 30.9	0.1	0	0	0.3	0.1	1.2	0	0.2	0.2	0.3	0.2
31.0 - 31.9	0.1	0	0	0	0.1	0.5	0	0.1	0.3	0.1	0.1
32.0 - 32.9	0	0	0	0	0.1	0.6	0	0.1	0.1	0.1	0
33.0 - 33.9	0	0	0	0	0	0.2	0	0	0	0	0
34.0 - 34.9	0	0	0	0	0	0.2	0	0	0	0	0

4.4 Monetary account of annual provision of ecosystem service

The monetary account measures the value of the benefit provided expressed in pounds. The cooling effect is monetised as the cost savings from air conditioning and the avoidance of heat-related labour productivity loss. The financial cost savings from air conditioning is calculated a share of the estimated GB level cost savings proportionally applied to each city region based on their GVA relative to GB. The avoided loss of labour productivity is monetised as the GVA that would have been lost due heat in the absence of the cooling effect. Table 12 shows the annual monetary value of the benefit across the 11 city regions. The size of the monetary value tracks to the size of the city region's economy, with southern cities such as London also being subject to a greater number of hot days avoided. The valuation results are dependent on the size of the effect being mitigated (i.e. hot days), which is subject to fluctuate year on year. This iteration of the accounts is based on a five year average number of hot days in each temperature band, between 2012 and 2016. For 2016, which experienced an above average number of hot days, a higher value of service was provided. In 2016, the total value of the service was £274m, of which the London City Region accounted for £233m.

Table 12: Total annual value of cooling from greenspace and bluespace in each of GB's city regions ('000£)[30]

	Total	Cardiff City Region	Edinburgh City Region	Glasgow City Region	Greater Manchester City Region	Liverpool City Region	London City Region	North East City Region	Sheffield City Region	West Midlands City Region	West of England City Region	West Yorkshire City Region
Annual value from avoided labour productivity loss	£159,396	£1,304	£110	£116	£3,909	£1,499	£135,560	£161	£2,115	£8,804	£2,931	£2,890
Annual value from air conditioning savings	£6,245	£149	£26	£26	£241	£241	£4,304	£26	£159	£483	£432	£159
Total Annual value	£165,641	£1,453	£135	£141	£4,150	£1,740	£139,863	£187	£2,274	£9,286	£3,363	£3,049

[30] The values found for avoided productivity loss are within a reasonably close range of the figures cited in Section 2.3. Compared to the finding that the 2003 European heatwave is estimated to have resulted in a reduction in manufacturing output in the UK of £400 to £500 million, the results here indicate a reduction in all sectors of £165 million in an average year. Compared to the analysis covering all economic sectors in London alone which predicted productivity losses for the 2080s of €1.9bn (2003 prices) (Costa et al., 2016), the results here indicate a value of £140 million for London (2017 prices), which if extrapolated over a 10 year period, would be equivalent to £1.4 billion.

4.5 Monetary account of future provision of ecosystem service

The monetary account of the future provision of the ecosystem service, or future benefit stream, accounts for the benefits received over a specified time period, in this case 100 years. This benefit stream accounts for the annual value projected over time factoring in any known trends which will affect the physical flow or monetary value of the benefits, and discounting the value stream to be presented in present days value, or Net Present Value. The account incorporates a projection for an annual increase in working day productivity losses due to climate change which increases the value of urban cooling over time. Table 13 presents the 100 year Net Present Value of the environmental assets for each city region.

Table 13: 100 year NPV of cooling from greenspace and bluespace in each of GB's city regions (£millions)

	Total	Cardiff City Region	Edinburgh City Region	Glasgow City Region	Greater Manchester City Region	Liverpool City Region	London City Region	North East City Region	Sheffield City Region	West Midlands City Region	West of England City Region	West Yorkshire City Region
100 year NPV	£11,156	£118	£28	£31	£352	£160	£9,038	£33	£222	£632	£245	£297

5 CONCLUSIONS AND RECOMMENDATIONS

This section provides a summary of the uncertainty associated with the accounting work and recommendations for maintaining and refining it.

5.1 Summary

The extension of the local climate change account has demonstrated an approach to incorporating urban blue space, private garden green space, and greater spatial granularity into the previously developed accounts (eftec *et. al*, 2017) which provide a more in depth understanding of the impact of this aspect of urban natural capital. Considerable benefit arises through the reduction of air conditioning costs and avoidance of labour productivity losses due to the effects of heat on those working in physically intensive construction jobs. The overall value of urban greenspace and bluespace across all 11 city regions was found to be £166 million annually (£159 million from avoided productivity loss and £6 million from avoided air conditioning costs), or £11.2 billion present value over the 100 year asset life. Further refinement of the accounts could provide greater robustness, some recommendations for subsequent iterations are found below.

5.2 Recommendations

The modelling of local climate regulation services from urban bluespace (rivers/canals, and lakes/ponds/reservoirs and additional greenspace (gardens) features marks an important development over the work done in the earlier scoping study (eftec *et al*., 2017), principally as it broadens out the scope of the urban natural capital assets that have been assessed. Similarly, to the earlier scoping work however, there are several caveats and limitations to the approach that could be addressed to improve the accuracy and robustness of the values emerging from the analysis. Key recommendations for this are outlined below.

Literature review to further refine the cooling effect values. A key limitation of the modelling approach used in this study is the relevance / applicability of the cooling effect values for different urban bluespace and greenspace features (and their buffer zones / 'distance decay' effect) used in the physical account modelling. This is a particular issue for non-linear bluespace features (lakes / ponds / reservoirs) where the best available evidence from O'Malley *et al*. (2015) was: (a) theoretical / simulation based; (b) somewhat unclear in terms of the exact nature of the polygon features that were assessed; and (c) did not include any values for the cooling effect adjacent to the features (i.e. 'distance decay' within the buffer zone). Also, the values used for linear features were from one empirical study looking at a specific UK river and therefore not canals. To address these limitations, a ***systematic literature review***[31] should be undertaken to, as far as possible, obtain robust, empirical cooling values for specific linear (river / canal) and other (lake / pond / reservoir) urban bluespace features, and for greenspace features such as private gardens, for which minimum size thresholds and distance decay-effects within buffer zones have not been studied, specific to the UK context. This should include consideration of size thresholds with specific cooling values obtained for different size / width classes of feature, to allow for more granular physical account modelling, similar to that adopted in the scoping study for urban woodlands and parks (eftec *et al*., 2017). In summary, the systematic literature review should seek to obtain robust values for all classes of urban bluespace feature for all of the indicators listed in Table 2.

[31] As a systematic review of the literature was not conducted for this study it is unknown whether substantial literature on these values exists, or whether there is a genuine gap in understanding that needs to be filled with original research.

Consideration of seasonality effects. While cooling provided by natural capital is a recognised benefit in summer, the effects of natural capital in winter are largely more uncertain. Trees can prevent radiative heat loss from the ground in winter, thereby reducing frost and ameliorating local winter temperatures, but may also reduce warming of the ground by weak winter sunlight. These and other processes may have both positive and negative impacts on winter energy use for domestic heating, which has not been studied in the UK. However, the i-Tree Eco software developed by the US Forest Service does assess seasonality aspects within its 'energy effects' module[32]. Although this aspect of i-Tree Eco is not well calibrated for the UK context (due to different building construction practices in the US and the UK), it could potentially be used to provide a relatively crude assessment of seasonal cooling / warming provided by natural capital.

Commission empirical research to fill remaining gaps. Following the outcomes of the literature review discussed above, any critical outstanding gaps in the evidence base concerning cooling values for different urban bluespace (i.e. the indicators in Table 1) and greenspace features should be addressed via new empirical research undertaken in the UK context.

Value of air condition cost and carbon savings. A refined approach to estimating the cost savings from reduced air conditioning use due to urban cooling may improve the accuracy of the estimate of these savings. Greater understanding is needed of the air conditioning usage in the city regions, in particular the degree to which air conditioning capabilities are present (likely declining towards the more northern regions), and how usage responds to changes in temperature, especially at the temperature ranges towards the lower usage thresholds, which was not considered in this study (i.e. 20ºC >< 28ºC). Demand will also vary according to the residential and economic makeup of the city regions, which also may shift along with changing climate. Energy use should also be investigated, as urban vegetation humidifies air, which impacts on the efficiency of some types of air conditioning unit. Additionally, the cost of carbon associated with the energy production for air conditioning could also be investigated.

Adoption of a more granular, bottom-up approach to physical account modelling. Evidence shows that particularly in the case of linear bluespace features (rivers / canals) there is potential to adopt a more granular / bottom-up assessment of different cooling effects (T_{urban} - T_{blue} in ºC) accounting for variation in urban form and design along the corridor associated with the linear features (see section 2.2 for an explanation of relevant concepts). This approach was beyond the scope of the current study due to the GIS processing required (e.g. processing of detailed spatial indicators of urban form in order to characterise and delineate different segments of the river / canal corridor). The key conceptual assumption here is that cooling values (i.e. T_{urban} – T_{blue} in ºC) in the river / canal corridor will vary depending on the nature of the urban form in the corridor. This concept was evidenced empirically for the River Don (Sheffield, UK) in Hathway and Sharples (2012). Although not identified specifically in the evidence review, this concept is also likely to be relevant to other bluespace features (lakes, ponds etc) and greenspace features as well (parks, urban woodland etc), especially due to prevailing wind deformation of the cooling boundary[33]. In relation to linear bluespace features, in principle a more granular, bottom-up assessment of cooling in the river corridor could be undertaken that takes this into account. The main constraint is the GIS analysis required to assess and categorise urban form typology in the river corridor, particularly if this is to be conducted at national scale. A sequence of possible steps for conducting this type of more bottom-up analysis are outlined below:

4. GIS analysis to model and delineate spatially the extent (i.e. segments of the river corridor) that can be allocated to a typology of urban form. For example, interactions between urban form and cooling for the River Don (Sheffield, UK) have distinguished

[32] https://www.itreetools.org/eco/overview.php

[33] As pers. comm. Kieron Doick, 2018.

between ‘open square’, ‘open street’, ‘closed street’ and ‘enclosed’ categories within an overall typology of river corridor urban form (see Hathway & Sharples 2012). Spatial delineation by economic activity could also inform more refined estimates of impact on productivity.

5. Calculate the area (absolute) and percentage of the buffer (i.e. river corridor) comprised of different categories of urban form from the typology in (1) – the percentage values (%) would be for whichever geography was being assessed in the account (e.g. whole of the UK, a specific city).
6. Calculate net values for buffer T_{urban} – T_{blue} in ºC based on the values for different urban form categories. There is some UK-based empirical data on cooling effect within the river corridor under different types of urban form in Hathway and Sharples (2012). The same proportional approach as per steps (3) and (4) in the physical flow account (see section 3.3) would then be applied to ascertain the net cooling effect of linear bluespace features based on the range of cooling values provided given different urban form / design conditions within the river corridor.

Expand the urban extent beyond the 11 city regions. A future study should seek to incorporate a greater proportion of GB’s urban extent. Ideally this would make use of real data, but alternately a means of uplifting could be applied with reasonable confidence with calibration.

Monitor trends in temperature, and the impact that they have on the value of natural capital. As the model is focused on investigating the avoided impact of hot days, the number of hot days in a given year plays a significant factor in the overall value of the natural capital asset on any given year. By updating the model on a regular basis, the effect of these temperature trends on the overall value of natural capital can be monitored and tracked over time. This is particularly relevant in the context of climate change, and a more robust approach to estimating the future impact of climate change on productivity, and the ability of natural capital to mitigate this, would improve the accuracy of the model.

REFERENCES

Bowler, D.E., Buyung-Ali, L., Knight, T.M., and Pullin, A.S., (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape Urban Planning*, 97(3), pp.147–155.

Costa, H., Floater, G., Hooyberghs, H., Verbeke, S., and De Ridder, K. (2016). Climate change, heat stress and labour productivity: A cost methodology for city economies. Grantham Research Institute on Climate Change and the Environment Working Paper No.248. London: LSE

eftec, CEH, CEP, University of Exeter, Peter Neal Consulting, Countryscape (2017). A Study to Scope and Develop Urban Natural Capital Accounts for the UK. *Prepared for the Department for Environment, Food & Rural Affairs*.

CICES (2013). Towards a Common International Classification of Ecosystem Services (CICES) for Integrated Environmental and Economics Accounting: V5.1. *European Environment Agency*.

Gill, S.E., Rahman, M.A., Handley, J.F., Ennos, A.R. (2013) Modelling water stress to urban amenity grass in Manchester UK under climate change and its potential impacts in reducing urban cooling. *Urban Forestry & Urban Greening,* 12 (3), p.350-358.

Gunawardena, K.R., Wells, M.J., and Kershaw, T. (2017). Utilising green and bluespace to mitigate urban heat island intensity. *Science of the Total Environment*, 584-585, pp.1040-1055.

Hathway, E.A., and Sharples, S. (2012). The interaction of rivers and urban form in mitigating the Urban Heat Island effect: A UK case study. *Building and Environment*, 58, pp.14-22.

Hou, P., Chen, Y., Qiao, W., Cao, G., Jiang, W., and Li, J. (2013). Near-surface air temperature retrieval from satellite images and influence by wetlands in urban region. *Theoretical and applied climatology*, 111(1-2),pp.109-118.

Hough, M.N., and Jones, R.J.A. (1997). The United Kingdom Meteorological Office rainfall and evaporation calculation system: MORECS version 2.0-an overview. *Hydrology and Earth System Sciences*, 1, pp.227-239, doi:10.5194/hess-1-227-1997.

Ishii, A., Iwamoto, S., Katayama, T., Hayashi, T., Shiotsuki, Y., Kitayama, H., Tsutsumi, J.I., and Nishida, M. (1991). A comparison of field surveys on the thermal environment in urban areas surroundings a large pond: when filled and when drained. *Energy and Buildings*, 16(3-4), pp.965-971.

Kjellstrom, T., Holmer, I., and Lemke, B. (2009). Workplace heat stress, health and productivity – an increasing challenge for low and middle-income countries during climate change. *Global Health Action*, 2, pp.46-51.

Kleerekoper, L., van Esch, M., and Salcedo, T.B. (2012). How to make a city climate-proof, addressing the urban heat island effect. *Resources, Conservation and Recycling*, 64, pp.30–38.

Manteghi, G., Bin Limit, H., and Remaz, D. (2015). Water bodies and urban microclimate: A review. *Modern Applied Science*, 9(6), pp.1-12.

Murakawa S., Sekine T., and Narita, K. (1990). Study of the effects of a river on the thermal environment in an urban area. *Energy and Buildings*, 16(3-4), pp.993-1001.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Boorman, P.M., Booth, B.B.B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Howard, T. P., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., and Wood, R. A. (2009). UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter.

O'Malley, C., Piroozfar, P., Farr, E.R.P., and Pomponi, F. (2015). Urban Heat Island (UHI) mitigating strategies: a case-based comparative analysis. *Sustainable Cities and Society*, 19, pp.222–235.

Robinson, E.L., Blyth, E.M., Clark, D.B., Finch, J., and Rudd, C. (2017). Trends in atmospheric evaporative demand in GB using high-resolution meteorological data. *Hydrology and Earth System Sciences*, 21, pp.1189-1224.

Robinson, E.L., Blyth, E., Clark, D.B., Comyn-Platt, E., Finch, J., and Rudd, A.C. (2017). Climate hydrology and ecology research support system meteorology dataset for GB (1961-2015) [CHESS-met] v1.2. NERC Environmental Information Data Centre. https://doi.org/10.5285/b745e7b1-626c-4ccc-ac27-56582e77b900

Robitu, M., Musy, M., Inard, C., and Groleau, D. (2004). Energy balance study of water ponds and its influence on building energy consumption. *Building Service Engineering Research Technology*, 25(3), pp.171–82.

Rogers, K., Sacre, B., Goodenough, J., and Doick, K. (2015). Valuing London's Urban Forest - Results of the London i-Tree Eco Project [online]. Available at: https://www.forestry.gov.uk/pdf/2890-Forest_Report_Pages.pdf/$FILE/2890-Forest_Report_Pages.pdf [accessed 05/05/17]

Santamouris, M., Ding, L., Fiorito, F., Oldfield, P., Osmond, P., Paolini, R., Prasad, D., and Synnefa, A. (2017). Passive and active cooling for the outdoor built environment – Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. *Solar Energy*, 154, pp.14-33.

Steeneveld, G.J., Koopmans, S., Heusinkveld, B.G., and Theeuwes, N.E. (2014). Refreshing the role of open water surfaces on mitigating the maximum urban heat island effect. *Landscape and Urban Planning*, 121, pp.92-96.

Sun, R., Chen, A., Chen, L., and Lü, Y. (2012). Cooling effects of wetlands in an urban region: The case of Beijing, *Ecological Indicators*, 20, pp.57–64.

Theeuwes, N.E., Solcerová, A., and Steeneveld, G.J. (2013). Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city. *Journal of Geophysical Research: Atmospheres*, 118, pp.8881–8896.

Tumini, I. (2014). The urban microclimate in open space. Case studies in Madrid Ph. D. Thesis. Escuela Técnica Superior de Arquitectura de Madrid, Spain.

Volker, S., Baumeister, H., Classen, T., Hornberg, C., and Kistemann, T. (2013). Evidence For The Temperature-Mitigating Capacity Of Urban Blue Space – A Health Geographic Perspective. *Erdkunde*, 67(4), pp.355-371.