# Urban Green Infrastructure

## Summary

***Key policy messages***

This case study looks at the outcome in the 25 Year Environment Plan (25YEP) to 'green our towns and cities by creating green infrastructure'. We refer to green infrastructure as GI in this document. This case study considers the potential effect of climate change on the outcome (creating more GI), but also how climate change might alter the demand for GI, due to its adaptation benefits, and thus make the outcome potentially easier to achieve.

The first key policy message is that the current Government goal for increasing green infrastructure has largely ignored the potential effects of climate change on the outcome, and the role of GI for adaptation. This is highlighted as a gap. In terms of the actual 25YEP outcome, the analysis finds it is unlikely that climate change will make the actual delivery of the 25YEP goal for more GI (in terms of hectares or number of schemes) more difficult to achieve, because it won't affect the introduction of schemes directly. However, climate change could 1) affect the anticipated benefits of GI, and 2) alter the future demand for GI (making the original outcome more likely to be achieved). For the first of these effects, the study finds that climate change is likely to have a fairly modest negative impact on most of the ecosystem services provided by GI (amenity, physical health) but could have important implications on its adaptation benefits. There is little evidence on the size of these effects, but a recommendation is that 'climate smarting' new GI could be beneficial (although further analysis to understand the costs and benefits of this is recommended).

For the second effect, climate change is projected to increase the demand for some of the broader ecosystem service benefits provided by GI, notably recreation: this could enhance the demand and potentially uptake of GI in a warmer climate, making the Government outcome easier to achieve. Climate change could also, more obviously, increase the demand for urban adaptation, through autonomous or planned action, but this will only lead to an increased implementation of GI if this option has benefits over conventional adaptation options. To investigate the latter, the study has investigated the effectiveness of GI for adaptation, and its costs and benefits, relative to other urban options. This finds that when only GI adaptation benefits are considered, e.g. cooling benefits, GI options are not that favourable in cost-benefit terms. However, when GI co-benefits are included (i.e. recreational, other ecosystem services), then economic benefits increase, and there is a higher justification (in economic terms) for GI schemes. This points to the need for GI to be advanced as options that address multiple objectives (rather than as exclusively adaptation options). Finally, the current policy focus for GI is on design standards, but an analysis in the review identifies that there are other barriers that need to be addressed to incentivise scale-up.

***What is the outcome?***

The 25YEP (HMG, 2018) sets out a policy to green towns and cities by creating (urban) green infrastructure and making sure there are high quality, accessible, natural spaces close to where people live and work. The 25YEP states that the introduction of green infrastructure (new, upgrading and retro-fitting) is aimed at improving health and mental well-being (as the primary objective and benefit). It is highlighted that the 25YEP outcome is not specific and there are no quantitative targets (e.g. area or number of schemes).

This case study is different to the others, because it involves two separate questions.

1. The first question is whether climate change will affect the delivery of the Government outcome, i.e. the goal to increase the amount of Green Infrastructure (GI) and deliver health and well-being benefits.

2. The second question relates to whether climate change will itself increase the demand for GI, because of the adaptation benefits it can provide, which could in turn make the Government outcome (to increase GI) easier to achieve.

The analysis has therefore considered both of these.

The first part of this case study assesses if climate change could make the delivery of the 25YEP outcome, to '**Green our towns and cities by creating green infrastructure'**, more difficult to achieve, i.e. in terms of hectares or numbers of schemes, and the anticipated benefits of the goal (health and well-being, as set out in the 25YEP). It subsequently considers what additional action might be needed to make green infrastructure climate smart (to future climate change) to ensure the increase in GI delivers its anticipated benefits.

However, urban green infrastructure is also a form of ecosystem-based adaptation. The second part of the case study therefore assesses whether climate change could increase the demand for green infrastructure as an urban adaptation option, and thus make the 25YEP outcome easier to achieve. These demand effects might relate to the direct adaptation benefits of GI (e.g. cooling, flood risk management) but it also might arise from increased demand for other GI benefits (e.g. urban recreation).

While there are a large number of potential urban GI options, the study has focused on urban green spaces (e.g. parks), green roofs, and urban flood management including sustainable urban drainage systems.

### *How does climate change affect the outcome, in a 2 vs 4°C pathway?*

Does climate change make the green infrastructure target in the 25YEP more difficult to achieve?

The first finding is that the 25YEP goal for green infrastructure does not take climate change into account, i.e. it does not consider the potential impact of climate change on GI, nor the role for GI as an adaptation option. This is highlighted as an important gap.

Turning to the first question, it is unlikely that climate change would make the actual 25YEP outcome itself more difficult to achieve, i.e. in terms of hectares or numbers of schemes. However, climate change could affect the anticipated benefits of GI. To investigate this, the study has assessed the function of green infrastructure, then the potential effects of climate change on these.

Green infrastructure provides 'ecosystem services', i.e. provisioning, regulating, cultural and supporting services. For urban GI, these include amenity and recreational value; improved physical health and mental well-being; social cohesion; air quality improvements; and $CO_2$ sequestration, but they also include adaptation benefits, from reducing urban heat island (UHI) effects and reducing water runoff/managing flood risks (Demuzere et al., 2014; Matthews, 2015). Some schemes are primarily introduced for amenity benefit, but have adaptation co-benefits (e.g. green spaces), while others are targeted at climate risks but have ecosystem service co-benefits (e.g. sustainable urban drainage) (McVittie et al., 2017). There is relatively little literature on the potential effects of climate change on green infrastructure, with only a small number of specific assessments (e.g. de Sousa et al., 2016; Sarkar et al., 2018). However, there are already current impacts of climate extremes (notably storms) on urban green spaces (e.g. Prichard, 2012), and there is also the potential that changing extremes (windstorms, heat extremes, and droughts) could increase damages to GI (Defra, 2018) or exceed its functional range (Dadson et al, 2017). Furthermore, there is a wider literature on the impacts of climate change on the natural environment (forests, plant species) (e.g. Brown et al., 2016) and based on this, it is possible that climate change could affect the climatic suitability of particular species used for green infrastructure (in a particular location). However, climate change may also lead to benefits, e.g. the climate projections forecast extended growing seasons and there are potential $CO_2$ fertilisation effects, which might enhance some GI benefits, although this would increase maintenance costs for vegetative control (Hudson, 2003). This case study has mapped the potential impact of climate change on each of the ecosystem services provided by green infrastructure, based on a literature review. We find that climate change has highest potential impacts on adaptation services, and $CO_2$ sequestration potential, with lower potential impact on amenity and physical / mental health. These effects are likely to be greater in a 4°C pathway, though in the short to medium-term a greater difference is likely to arise from uncertainty in the projections (i.e. the 10th to 90th range in UKCP18, Lowe et al., 2018). In the short-term, the review identifies the largest effects are likely to arise from changes in extremes. If these impacts are not considered, therefore, climate change could alter the effectiveness of GI.

Thresholds and lock-in. As natural systems, green infrastructure will have thresholds associated with bioclimatic suitability levels and extreme tolerances (heat, dry spell duration). Based on the literature on climate change and UK ecosystems (Brown et al., 2016), these thresholds are more likely to be exceeded in a 4°C world. New GI also involves land-use change and therefore lock-in. The design of GI includes species choice (of plants) as well as engineering design, and therefore needs to consider the implications of future climate. This involves some challenges due to uncertainty (to a 2 and 4°C world or to the 10th to 90th percentile uncertainty range within a particular emissions scenario), especially because of the long life-times involved (e.g. for tree species). However, the level of irreversibility is generally lower for GI than for grey infrastructure, as the latter has high capital costs and is often difficult and costly to change later (ECONADAPT, 2017), and thus GI may offer greater adaptation flexibility. With the 25YEP goal to increase GI, there is an opportunity to introduce climate risk screening for GI design, i.e. using similar methods to those being implemented for grey infrastructure (see later case study).

Does climate change affect the demand for green infrastructure and its level of uptake?

The case study has assessed whether climate change could affect the demand for services that GI provides. First, the review has considered non-climate GI ecosystem services. Under a warmer climate, there is likely to be greater outdoor recreational demand, which could increase the demand for urban green areas and GI. Climate change does have potential effects on air pollution (Hames et al., 2012; Vautard et al., 2015). However, green infrastructure is not seen as a major option for reducing air pollution in current air quality policy (e.g. see Defra, 2019b): while some studies report that GI could have air quality benefits (Fairbrass et al., 2018) others highlight these are likely to be temporary due to resuspension (Defra, 2010). Climate change mitigation policy, especially under new net zero targets (CCC, 2019) will increase the demand for $CO_2$ sequestration, however, urban green space is relatively ineffective at sequestration at scale compared to other options, and would also have low cost-effectiveness as a sequestration option due to high urban land-use prices (though rural green areas will be key to delivering net zero emissions).

More obviously, climate change could also increase the demand for urban adaptation. This could in turn increase the demand for green infrastructure, and therefore make it easier to achieve the 25YEP goal (for more GI). The increased uptake of GI could possibly happen reactively (autonomous) due to the changing climate, but due to the barriers to uptake (see later), it is considered more likely that it could increase as a result of planned adaptation policy. However, for this to happen, GI would need to have net benefits over other adaptation alternatives, in keeping with standard government options and policy appraisal (HMT, 2018). It is noted that the level of increased demand (and relative performance) could be different under a 2 vs 4°C pathway. To expand, rising urban heat is likely to incentivise the uptake of cooling options, but the uptake of GI as an adaptation option to address this alone will depend on the relative costs and benefits (compared to alternatives), and subsequently whether there are incentives to increase uptake (see next section). Increasing heavy precipitation could also increase the demand for urban flood management, but there are some studies that highlight the limits of natural flood management (Dadson et al, 2017), i.e. it is unclear if a changing climate in itself would increase or decrease the attractiveness of green (vegetated) SuDS as an option for reducing risk.

***What are the economic costs of climate change, i.e. the effect on the outcome?***

Economic costs of climate change on GI. The quantified economic benefits of green spaces are dominated by their recreational and aesthetic benefits (e.g. Holzinger et al., 2014: Dennis and James, 2016). Climate change is likely to have a relatively modest impact on recreational potential: though there are potential costs from extreme events on GI, leading to reduced access, as well as restoration and repair costs, notably from wind-storms and droughts. Climate change could also affect the costs of maintaining GI, because of vegetative growth and higher maintenance costs. One study suggests (Hudson et al., 2003) that maintenance costs could increase significantly by mid-century (20% by the 2020s, 30% to 40% by the 2050s) compared to current (though these might well be offset by additional benefits, i.e. enhanced sequestration).

Change in demand (for non-climate ecosystem services). It is more difficult to estimate how much climate change might affect the demand for broader ecosystem services associated with GI, how this translates into additional GI demand, and the economic costs or benefits of this. There is some indication it could increase outdoor recreational demand, for example, from rising tourism activity in the UK (e.g. Ciscar et al., 2014), although these studies focus more on non-urban effects. Climate change will increase the demand for $CO_2$ sequestration, especially under more ambitious mitigation scenarios (such as net zero, CCC, 2019) and climate change has the potential to actually increase sequestration benefits of GI (from longer growing seasons and $CO_2$ fertilisation (Hudson, 2003), however, as above, urban sequestration does has lower cost-effectiveness than rural options. Climate change could have some potential impacts on air quality, notably with the potential to increase ozone (Hames et al., 2012), but existing air quality legislation and policy focus on reducing air pollution means that future air pollution (e.g. by 2040) will be very much lower than today, thus overall demand for air quality improvements will be much lower.

Change in demand for climate related ecosystem services. Climate change could clearly increase the demand for urban adaptation, which could include urban GI. This is explored further below.

***What are the potential additional adaptations options to address impacts on the outcome?***

The case study has looked at two types of adaptation, the first focused on protecting GI investments and the second on GI as an adaptation option in its own right.

Adaptation options to make green infrastructure climate resilient. There are a number of potential options to make GI climate smart, though these are often quite specific to the particular scheme. There has been some analysis of the use of more resilient plant species (e.g. de Sousa et al., 2016) and enhanced management of green areas, examples being species choice to make green roofs more drought-resistant or SuDS that are better able to cope with increased heavy precipitations/ peak flows. For tree species, there is the existing forestry adaptation literature. (Frontier Economics et al., 2013b; Forestry Commission; Tree Health Resilience Strategy (Defra, 2018c)).

Green infrastructure as an adaptation option. The role of green infrastructure as an adaptation option requires an analysis of the relative attractiveness compared to other options. While effectiveness is site, context and location specificity, the literature suggests:

- There are a range of urban green options that move in scale from small-scale urban planting through to major urban green spaces. The literature reports that cooling benefits from green space options could reduce local temperature by 1- 2°C (Tapper, 2019: Bowler et al, 2010; Kingsborough et al. 2017), although some studies report higher values at the localised scale (Coutts et al., 2016a: Coutts et al., 2016b; Thom et al., 2016), or if very large areas of urban land are converted to green.

- There is more literature on green roofs. These provide multiple benefits, including reduced heating demand, but they can also include cooling benefits. However, the reported cooling potential of green roofs varies. There are some studies that report very high cooling within buildings (internal temperatures) especially for systems designed for hot climates (e.g. Coutts et al., 2013), however, within the UK, benefits are often based on reducing winter heating demand (not summer cooling). There are also studies that look at the potential ambient cooling of green roofs i.e. outdoors (e.g. Satamouris, 2014), which find low or negligible low levels of ambient cooling, although other studies (e.g. Meyers et al. 2015)) that assume very high take-up of green roofs find higher results (noting that while this may be possible for new developments, it not realistic for the existing English housing stock).
- There are also a number of natural flood management options, although many of these focus on coastal and rural options. In the urban context, green SuDS are the main option (while noting the green areas above have potential for some flood management). There are some studies that identify an effective role for urban natural flood management and for nuisance flooding (Frontier Economics, 2013c), but other studies highlight the limits of natural flood management for more major flood events (Dadson, 2017; McVittae et al, 2017.

Mapping green infrastructure to the early priorities for adaptation. The study has also considered how GI aligns to the three early priorities for adaptation.

- No and low-regret. GI has considerable potential as a win-win option, due to the wide number of co-benefits (see earlier analysis of ecosystem services).
- Early decisions with a long life-time. There is a good argument for making new GI climate resilient, noting this would be easier if undertaken during design, and that it may have greater flexibility than grey infrastructure (but that it might not (on its own) provide high levels of resilience for major extreme events).
- Early preparation for long-term climate change. Urban heat in major cities in England is likely to be a major future issue, and there is a very strong case for enhancing the analysis, research and monitoring of urban greenspace and UHI, and using information to feed back into policy.

Barriers. The study has assessed why the uptake of urban GI in England has been low to date, to help understand additional adaptation that could help enhance uptake. A number of barriers have been identified (Byrne and Yang, 2009; Demuzere et al., 2014; Watkiss and Cimato., 2017), including information barriers; institutional barriers; policy barriers and financial and economic barriers. The case study has looked at the role for adaptation to address these barriers, and enhance uptake, drawing on some of the literature for success factors for ecosystem-based adaptation (Ecofys, 2017). An important finding is that additional adaptation action is needed to deliver GI adaptation, and enhance the role for GI as an adaptation option.

***What are the benefits and potential costs of adaptation?***

The final section looks at the potential costs and benefits of adaptation. Following from the section above, this considers two assessments. First, the costs and benefits of climate smarting green infrastructure. Second, the costs and benefits of green infrastructure as an adaptation option.

Options to make green infrastructure climate resilient. There is very little information to allow a cost-benefit analysis of climate-smarting new green infrastructure, although there are some relevant lessons from the forestry sector (e.g. Frontier Economics et al., 2013c) for green spaces.

Green infrastructure as an adaptation option

The case study has reviewed the literature on costs and benefits of green infrastructure options.

- The benefit to cost ratio of green urban spaces shows a large range, which are very site and context specific, however, studies report that recreational benefits dominate the current benefits

(Holzinger et al., 2014: Dennis and James, 2016) and cooling benefits are currently low in economic terms. The analysis of the costs and benefits of green space as an adaptation option (Liu et al. 2016; Mendizabal and Peña, 2016, Loibl et al, 2015) do show positive benefit to cost ratios (BCRs) for small urban schemes, driven by the overall benefits (not just cooling). However, they often find new green space has low benefit to cost ratios, due to the high opportunity costs associated with land-use (and land-use values) in major urban centres, where land has to be used to make room for the new GI. This means that it can be more difficult for schemes to be economically justifiable based on adaptation benefits alone (although green space can increase property values around the scheme) especially as the larger cooling benefits arise in the future, and are low in present value terms after discounting. It is more likely that schemes can be justified when all ecosystem service benefits are included. Smaller schemes can address some of the cost barriers, but have much lower / or more localised cooling effect.

- There are some studies of the benefit to cost ratio for green roofs (Nurmi et al., 2013: Meyers et al., 2015; Mahdiyar et al., 2016: Bouwer et al., 2018). In most cases, these show low benefit to cost ratio, with a low proportion of these benefits from adaptation (internal cooling). Further, many of these benefits are non-market in nature, and thus their private financial attractiveness is low.
- The benefit to cost ratios of SuDS have been studied (e.g. Ossa-Moreno et al. 2017), and guidance existing for estimation (Benefit of SuDS Tool (BeST) (UKCIRIA)), although the financial case alone does not appear to incentivise adaptation.

Overall, the economic analysis highlights that these options do not have significantly greater attractiveness than conventional adaptation options, but this is partly because the economic analysis tends to penalise many of the characteristics of GI (slow establishment and lower early benefits, discounted long-term benefits). Further, many of their benefits arise from non-market value, which makes them less attractive from a private investment viewpoint. When the full range of benefits are included – particularly the more intangible but real non-market values such as health, amenity, recreational, cultural and environmental regulatory benefits – they have positive benefit to cost ratios. This points to the need for GI to be advanced as options that address multiple objectives (rather than as exclusively adaptation options).

## Step 1. What is the objective and outcome?

***Outcome***

Chapter 3 of the 25 Year Environment Plan (25YEP (HMG, 2018) focuses on 'Greening our towns and cities' and sets out policies for:

- Creating more green infrastructure; and
- Planting more trees in and around our towns and cities.

There is also a specific target for 'Making sure that there are high quality, accessible, natural spaces close to where people live and work, particularly in urban areas, and encouraging more people to spend time in them to benefit their health and wellbeing'. The introduction of green infrastructure (infrastructure in new developments, upgrading of existing green infrastructure and retro-fitting of new green infrastructure) set out in the 25YEP is primarily focused on health and mental well-being (health and happiness), and the ancillary benefits of social cohesion. The primary goal is not adaptation. Moreover, the outcome set out in the 25YEP is not specific: there is no target on the area of greenspace[1]. Against this background, this case study has looked at two issues.

1. The first part of this case study assesses if climate change could make the delivery of the 25YEP outcome, to 'Green our towns and cities by creating green infrastructure', more difficult to achieve. This also considers what might be needed to make green infrastructure climate smart (to future climate change) to ensure the increase in GI delivers its anticipated benefits (as set out in the 25YEP).
2. However, urban green infrastructure is also a potential adaptation option – some schemes are primarily introduced as adaptation (known as ecosystem-based adaptation), while others have ancillary adaptation benefit. The second part of the case study therefore assesses the role of green infrastructure as an urban adaptation option. In this case, climate change may incentivise the uptake of GI, due to increased demand for urban adaptation, which could also make the 25YEP outcome easier to achieve. Climate change could also alter the demand for other services that GI provides, e.g. recreation, which might also increase demand for GI. However, the role of green infrastructure for adaptation will depend on its relative performance over grey adaptation infrastructure.

These issues are inter-linked and they are complex, especially because the 25YEP outcome is associated with area/number of green infrastructure schemes, while benefits depend on effectiveness, which is extremely type, location and context specific.

The underlying Government theory of change for the 25 YEP outcome might look like the following:

- Activities: Research is carried out to improve understanding around GI costs and benefits;
- Outputs: An enabling environment (including regulatory and policy framework and guidelines for practitioners) is created to facilitate GI investment;
- Outcomes: England's infrastructure comprises an optimal mix of grey and GI infrastructure providing a range of benefits to its inhabitants;
- Impact: England GI contribute to England's welfare.

For the second area of focus, the role of GI for adaptation, a separate theory of change and a separate adaptation outcome would be relevant (improve the resilience of the country against climate risks).

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[1] Note that the 25YEP also has a goal to plant one million trees in England's towns and cities by 2022, although this is not the focus of this case study.

The delivery of the 25YEP goal will be advanced by others, though the Government can incentivise greater uptake of GI. The main Government route for delivery at present is by defining a set of standards (national framework of green infrastructure standards) in close consultation with stakeholders, including the Parks Action Group. This should 'ensure' (though it is not clear if this will be mandatory) that new developments include accessible green spaces and that any area with little or no green space can be improved for the benefit of the community. It also highlights the linkages with the Industrial Strategy, and the important contribution made to economic growth by high-quality environmental assets and green infrastructure. To achieve this Outcome, the Plan commits to a number of actions:

- 'Supporting the Parks Action Group in its work to help England's public parks and green spaces meet the needs of communities now and in the future.
- Continuing our ground-breaking work with Exeter University to update the world-leading Outdoor Recreation Valuation Tool (ORVal) in 2018.
- Establishing a cross-Government project, led by Natural England, that reviews and updates existing standards for green infrastructure by summer 2019.
- Supporting Local Authorities to assess green infrastructure provision against these new standards.
- Working with the Ministry of Housing, Communities and Local Government to see how our commitments on green infrastructure can be incorporated into national planning guidance and policy.
- Continuing to work with stakeholders to develop and implement a programme to plant one million trees in England's towns and cities by 2022.
- Working with stakeholders to develop and implement a manual for local authorities and other urban tree-planting organisations to shape their procurement and maintenance practices for urban trees.
- Introduce new requirements to ensure councils properly consult if they are considering removing street trees'.

The 25 YEP also has a policy of 'putting in place more sustainable drainage systems'. The main actions to deliver this are:

- Amending Planning Practice Guidance to clarify construction and ongoing maintenance arrangements for SuDS in new developments, tightening links with planning guidance for water quality and biodiversity.
- Considering changes to the National Planning Policy Framework and Building Regulations in the longer term to encourage SuDS.
- Improving existing arrangements for managing surface water flooding, and the outcomes delivered by Lead Local Flood Authorities and other risk management authorities, including water companies.

In the NAP2, the key actions are for a set of Green Infrastructure standards will be developed to help local GI planners, designers, managers and communities deliver good quality GI. This includes:

- Undertaking an Evidence Review and consulting stakeholders;
- Developing a draft Model Framework of GI Standards;
- Test draft Framework through pilots;
- Producing guidance on planning and delivering Green Infrastructure, including applying the Framework of GI Standards;
- Launching mainstreaming and support to Local authorities, developers and others monitoring and evaluation.

**Green infrastructure and ecosystem service benefits**

Green infrastructure (GI) is a strategic, planned network of natural, semi-natural and artificial components designed and managed to deliver a wide range of ecosystem services and quality of life benefits (Fairbrass et al. 2018). For this case study, we focus on a number of urban green infrastructure measures:

- Green spaces. These include a range of environments and interventions, including parks, playing fields, woodlands, wetlands and street trees.
- Green roofs. These include specific green roofs (or walls) which integrate green into buildings (note that these are included in green spaces in the 25YEP, but we separate because of the differences in objective and costs and benefits.
- Green sustainable drainage systems (SuDS), such as permeable surfaces and ponds, which aim to reduce the risk of surface water flooding.

Note that for some green infrastructure, e.g. SuDS, climate related benefits are the primary objective of the intervention (flood management). For others, e.g. urban greenspaces, adaptation is an ancillary benefit or secondary objective.

In the 25 YEP the primary benefit outlined from green infrastructure is on health and well-being, but GI is a form of natural capital and has a number of benefits (Matthews, 2015). These include:

- Amenity value (recreational value);
- Improved physical health and mental well-being (health);
- Social cohesion;
- Air quality improvements (environment);
- $CO_2$ sequestration (mitigation).
- Adaptation benefits, for example by reducing urban heat island (UHI) effects and controlling water runoff, thereby reducing flood risks.
- Particular types of green infrastructure may have other benefits, e.g. green roofs reduce building energy demand for heating.

These benefits are often termed ecosystem services, and are categorised into provisioning, regulating, cultural and supporting services. These are shown in Figure 1 below.

The specific benefits vary with the type of urban GI. For example, some schemes are primarily for amenity benefit, but have adaptation co-benefits (e.g. urban greenspaces), while others are targeted at climate risks and thus are adaptation options that have ecosystem service co-benefits (e.g. sustainable urban drainage).

The goal to increase green infrastructure also need to be seen in the context of baseline changes. The CCC (2019) reports that urban green space declined between 2001 and 2018 from 63% to 55% of urban areas. CCC (2017 and 2019) reports that the uptake of sustainable drainage systems (SuDS) in new development appears to be low, as is the use of permeable paving. Regulations requiring local authorities to approve and adopt SuDS in new development have not yet led to high uptake: CCC (2017) reports that around 30% of the respondents (to a CIWEM survey) said that SuDS (of any type) were not used in all major developments.

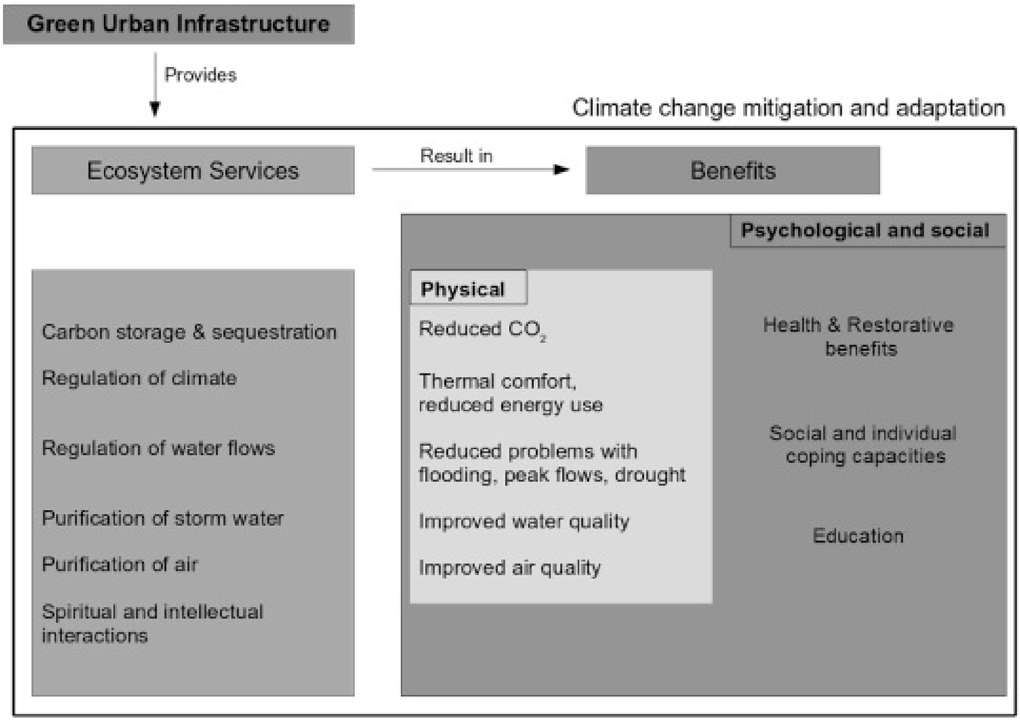


Figure 1 Green Infrastructure Ecosystem Service and Functions

*Source: Demuzere et al. (2014)*

McVittie et al (2017) also map services from individual urban green GI.

| | | | Urban Farming | Green spaces | Green Roofs | Urban forest parks | Trees in urban areas | Swales | Rain Gardens | Detention Basins | Retention Ponds | Infiltration basins |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Regulating | Mediation of waste, toxics and other nuisances | Mediation by biota | 🟩 | | | | | 🟩 | 🟩 | | 🟩 | |
| | | Mediation by ecosystems | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | | Mass flows | 🟩 | 🟩 | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | | Liquid flows | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | | Gaseous / air flows | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | Maintenance of physical, chemical, biological conditions | Lifecycle maintenance, habitat and gene pool protection | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | |
| | | Pest and disease control/Pollination | 🟩 | 🟩 | 🟩 | | | | | | 🟥 | 🟥 |
| | | Soil formation and composition | | | | | | | 🟩 | | | |
| | | Water conditions | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | | Reduction of GHG concentrations | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | | Micro and regional climate regulation | | 🟩 | 🟩 | 🟩 | 🟩 | | | | | |
| Cultural | Physical and intellectual interactions | Physical and experiential interactions | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | | Intellectual and representational interactions | | | | | | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |

🟩 +ve impact    No impact    🟥 –ve impact

Figure 2 Expected ecosystem service impacts of urban EbA measures. McVittie et al. (2017)

***Policy landscape***
Within the English planning system, the core policy framework for green infrastructure is primarily set through the National Planning Policy Framework together with its associated National Planning Practice Guidance (Scott et al. 2017).

- *National Planning Policy Framework.* The NPPF is the key planning guidance for the English planning system. It is linked with the thread of sustainable development which is the overriding purpose of the planning system.

- *National Planning Practice Guidance.* National Planning Practice Guidance (NPPG) is an important complement to the NPPF. In essence this is a web-based portal that translates the NPPF wording into priorities on the ground in terms of day to day practices of policy and plan development and planning application decisions.

## Step 2. How does climate change affect the outcome, in a 2 vs 4°C pathway?

The next step in the analysis is to assess whether climate change affects the outcome in a 2 versus a 4°C world. In line with the two issues highlighted above, this leads to two questions.

The first question (related to point 1 above) is to address is does climate change make the urban green infrastructure target in the 25YEP more difficult to achieve?

This leads to a second question (related to the point 2 above) of does climate change affect the attractiveness of green infrastructure and its level of uptake? subsequently affecting the outcome of greening towns and cities and thus indirectly affecting the achievability or even desirability of the target in the 25YEP.

**Does climate change make the green infrastructure target more difficult to achieve?**
Looking forward, it is unlikely that climate change would make the actual 25YEP outcome itself more difficult to achieve, i.e. in terms of hectares or numbers of schemes, because it won't affect the actual introduction of green infrastructure (at least from first order effects). However, climate change could affect the anticipated benefits of the green infrastructure, i.e. its subsequent impact (which in turn might affect its subsequent uptake, i.e. second order effects). A further issue is whether these first and second order effects would differ between a 2 vs 4°C pathway.

The starting point is to assess the impact of climate change on the ecosystem services that green infrastructure provides. As highlighted above (Demuzere et al., 2014), these include:

- Amenity value (recreational value);
- Improved physical health and mental well-being (health);
- Social cohesion;
- Air quality improvements (environment);
- $CO_2$ sequestration (mitigation).
- Adaptation benefits, for example by reducing urban heat island (UHI) effects and controlling water runoff, thereby reducing flood risks.
- Particular types of green infrastructure may have other benefits, e.g. green roofs reduce building energy demand for heating.

Climate change does have potentially large impacts on the natural environment, and many of these risks are relevant for green infrastructure. These include changes in the average climate (bio-climatic suitability range) and extremes (notably heat, drought, windstorms and heavy precipitation/floods), as well as indirect effects such as pests and diseases. UKCP18 (Lowe et al. 2018) reports on average and seasonal warming and precipitation. It also reports that summers as hot as in 2018 could be expected every other year by the middle of the century. Surface water flooding is also likely to increase, particularly in urban areas. UKCP18 also indicates drier summers, with more reductions in rainfall in the south, although there is a large uncertainty range around this. It also reports a projected increase in intensity of extreme wet days (the 99th percentile of daily precipitation), which is a key factor in flooding. UKCP18 reports that these changes are larger in a 4°C pathway, though in the short to medium-term, the greater threat is from the range of model uncertainty (the range from the 10th to 90th percentile for a given scenario), i.e. the importance of 4°C pathways is only likely to emerge after 2050. It is stressed that not all of these impacts would be negative, e.g. there could be extended growing seasons and $CO_2$ fertilisation effects that might actually be positive, although these might have further effects notably on maintenance.

There is a limited literature relating to the impacts of climate change on green infrastructure. There are two studies that explicitly address the bio-physical impacts of climate on green infrastructure: de Sousa et al. (2016) and Sarkar et al. (2018). Whilst their studies are species- and context-specific, they provide useful information.

The first, de Sousa et al. (2016), explored the impacts of successive simulated droughts and floods on two plant species *(Carex lurida* and *Liriope muscari*) commonly installed in green-infrastructure (GI) sites built in the urban northeast USA. These species have been introduced to England and can be found in urban locations. The instantaneous stomatal conductance, and below-ground biomass growth were used as metrics, since they are indicators of the ability of plants to provide ecosystem functions such as transpiration and carbon uptake. Their results show that both species had greater tolerance for floods than for droughts. Signs of stress were only evident after a simulated flood exceeding the duration of 95% of all storms that occurred in this geographic region between 1950 and 2000. By contrast, simulated droughts had a more pronounced effect on both the instantaneous conductance measures during drought and the recovery following the cessation of drought in both species.

The second, Sarkar et al. (2018), starts from the recognition that GI uses vegetation, soil, and distributed structures to manage rainwater where it falls and may provide greater flexibility for adaptation. The study explores how a warmer climate may affect performance of different types of GI. It uses a watershed model to investigate sensitivity of different GI practices to climate. Simulations examine 36 urban ‘‘archetypes’’ representing different development patterns (at the city block scale) of typical U.S. cities, regional climatic settings, and a range of mid-twenty-first-century scenarios. Results suggest regionally variable effects of climate change on the performance of GI practices for water quantity, water quality, and carbon sequestration though GI is still able to mitigate most projected future increases in surface runoff.

Interestingly, the NAP2 (Defra, 2018) actually highlights some potential effects. It reports that summer heatwaves can lead to a spike in demand for water at the same time as restrictions on water use are in place. If this is preceded by or accompanied by a period of low rainfall, drought triggers may be reached earlier. There are also issues regarding the mitigation of the effects of heatwave, if the heatwave coincides with a drought. For example, green infrastructure is an important mechanism in reducing the effect a heatwave has, but if the heatwave is accompanied by a drought there could be restrictions on how much (and potentially if any) water can be used to maintain the green infrastructure. During drought, the priority will be maintaining the public water supply for public health and critical national infrastructure.

There are also some studies that look at the effectiveness of green infrastructure, which could provide insights into how changes in effectiveness might translate into effects (positively or negatively). However, these are primarily based on area, i.e. they look at the level of effectiveness in reducing heat with increasing area of green space. For this analysis, we are more interested in how the change in effectiveness for a given area varies under climate change. For example, Gill et al (2007), using Greater Manchester as a case study, found that if green cover in high-density residential areas and town centres was reduced by 10 per cent, surface temperatures are projected to be 7°C or 8.2°C warmer by the 2080s High in each, when compared to the 1961–1990 baseline case; or 3.3°C and 3.9°C when compared to the 2080s High case where green cover stays the same.

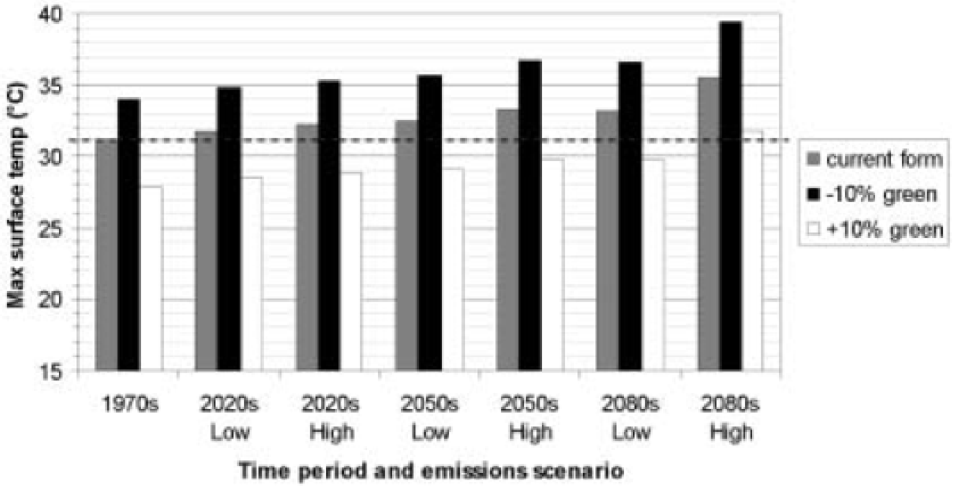


Figure 3 Maximum surface temperature for the 98th percentile summer day in town centres, with current form and when 10 per cent green cover is added or removed. Dashed line shows the temperature for the 1961–1990 current form case (Greater Manchester). *Source: Gill et al (2007)*

There is also recognition that there may be reduced functionality of GI from changes in heat, precipitation and other climate variables, as well as an increased range and prevalence of pest and diseases (Brown et al. (2016)). Similarly, there may be increased risks from extremes, windstorms, floods and extreme heat and dry spells. An example is the damage to trees in Kew Gardens, West London, caused by the windstorm of October 1987, during which, one-third of the trees in this urban park were brought down (Prichard (2012)).

Finally, an important aspect that has been captured in previous studies is that climate change could increase maintenance costs for managing green infrastructure, because of the extended growing season or $CO_2$ fertilisation (Hudson, 2003). The UKCP18 State of the UK climate report notes that the growing season has lengthened. This is already leading to additional costs as maintenance activity e.g. with local authorities reporting a higher number of cuts each to manage vegetation. The increase in temperature and growing season, could have implications for green management. This has been covered in some economic studies (see next section). Hudson, 2003 estimated that climate change would increase current vegetative maintenance costs by between 20% (2020s), 30% to 40% (2050s) and 50% to 70% (2080s) compared to current annual spend.

While it is highly indicative, the results of climate change on each ecosystem service function is shown below. Somewhat ironically, climate change is likely to have most effect on the adaptation benefits of green infrastructure, and less on the services around amenity and physical / mental health.

**Table 1 Potential risks of climate change on green infrastructure benefits**

| GI Ecosystem service benefit | Climate risk and evidence |
|---|---|
| Recreational benefits | Low. Some potential for reduced attractiveness of recreational activities, e.g. from loss or damage from droughts, windstorms, heat extremes), leading to loss or reduction of recreational impact or additional travel costs (to access alternative recreational sites). |
| Health benefits (physical health) | Low. As above |
| Mental health and well-being benefits | Low. As above. |
| Social cohesion | Low. As above. |
| Air quality improvement | Medium. Changes related to growth and regulating service effectiveness (as above). Climate change can affect air quality concentrations (notably ground level ozone) and potentially increase summer ozone: this has impacts on natural habitats. |
| $CO_2$ sequestration | Medium-high (relatively) related to ecosystem health. Potential positive effects from $CO_2$ fertilisation and longer growing season (more sequestration as higher growth) (Hudson, 2003). Potential negative effects if ecosystem health affected and reduced growth (from bioclimatic suitability or extremes) |
| Water regulation / improved water quality / flood management | Mixed. Note role for GI to reduce the climate risk. Potentially increase in heavy precipitation and flood enhance benefits of schemes, but there is also a potential risk if damaged or capacity overwhelmed (Dadson et al. 2017). Dry spells and drought might reduce scheme potential for flood management by impacting on ecosystem function. |
| Energy efficiency (cooling and heating) | High (positive and negative). Climate change will reduce winter heating degree days and heating demand reducing benefits (absolute) – this would reduce absolute energy efficiency benefit of green roofs in reducing energy losses. However, CC will increase summer cooling degree days and increase cooling demand, potentially increasing cooling benefit. |
| Reduced urban heat (and UHI) | High. CC will increase summer outside temperatures, affecting the risk of urban overheating, thus potentially higher benefits from GI. However, potential for reduced effectiveness if cooling function is reduced (e.g. from droughts, windstorms, water availability). Interlinkages with water availability – drought conditions may mean less water supply availability. |

**Thresholds and Lock-in**

The analysis has also considered the potential for thresholds and lock-in for green infrastructure. As natural systems, green infrastructure could have thresholds associated with the bioclimatic zones and suitability, as well as upper extreme tolerances (Settele et al., 2014). All plant and tree species have suitability ranges, and climate change may mean that current GI species move outside of optimal, and even tolerable, suitability ranges (with respect to the average temperature). The changing pattern of extreme levels may also lead to exceedances associated with levels above which damaging or lethal effects occur, especially the risk of extreme heat and also dry spell duration. These thresholds are more likely to be exceeded more in a 4°C world (Brown et al., 2016), as evidenced by the level of changes projected in UKCP18, but could also arise under higher warming outcomes for a given emissions trajectory, e.g. the 90th percentile range of high emissions in UKCP18.

New green infrastructure generally involves land-use change and therefore involves the potential for lock-in, although the level of irreversibility is much lower than for grey infrastructure. Nonetheless, a key issue is that the design of green infrastructure, including species choice as well as engineering design, needs to take account of the future climate, i.e. not to be designed based on the past. This involves some challenges, particularly for some elements (e.g. tree species choice) because of the long life-time involved.

Furthermore, it is often easier and more cost-effective to build adaptation into projects at the design and construction stage, rather than retrofitting later, because retrofitting is often more expensive, or in some cases, not possible.

It is also stressed that just like grey infrastructure, climate change uncertainty makes the up-front design challenging, i.e. to design green infrastructure that is resilient to both a 2 and 4°C world (or to the 10th to 90th range for a given emissions scenario the 2050s, for example).

However, this is one area where green infrastructure can have benefits over grey infrastructure, because it often offers more flexibility than grey. Some studies (e.g. de Bruin et al, 2012) highlight that it can be easier to update ecosystem-based adaptation over time, as compared to grey infrastructure. The reason for this is grey infrastructure tends to involve large up-front capital costs and involves a degree of irreversibility, i.e. it can be very costly to alter later (Fankhauser et al., 1999). In contrast, ecosystem-based approaches tend to have lower capital costs, but higher maintenance costs (Econadapt, 2017). This means they can be designed specifically to be updated later, with respect to changing conditions, at lower cost, as part of an iterative adaptive management approach, i.e. they offer greater potential for flexibility.

There is also a question on the limits of adaptation of other options (grey), especially to heat, which might mean that there is an imperative to enhance green infrastructure, as well as to prevent future irreversible loss.

**Does climate change increase the demand for non-climatic ecosystem services and GI uptake?**
The second aspect here is whether or not climate change itself could be a driver for the greater uptake of green infrastructure. This will be influenced partly by the issues above, but also by its relative performance compared to alternatives (especially on the adaptation side).

The first demand issue is to look at how climate acts as a driver for each of the ecosystem benefits associated with green infrastructure, not just the adaptation driver. This is more qualitative.

*Recreational demand.* Under a warmer climate, there is likely to be a shift in behaviour, which might include greater recreational demand, which could increase the demand for urban green areas. There are studies that look at future changes in the UK's climate and project benefits in terms of higher amenity value (e.g. Maddison (2003) and Maddison and Rehdanz (2011). There are also many studies that project that the UK could become a more attractive location for tourism (e.g. Hamilton et al., 2007; Ciscar et al., 2014). These imply that outdoor recreational demand could increase (even though they do not project the effect for greenspace directly).

*Air quality.* There are potential interlinkages between climate change and air quality, and some studies highlight the potential benefits of GI on removing pollutants (Fairbrass et al., 2018). However, GI removes pollutants from the atmosphere – it does not reduce them at emissions source. There is some research that suggests that the planting of trees along the sides of roads could reduce $NO_2$ concentration (Xu, 2008). Trees can also remove pollution by intercepting airborne particles. However, as highlighted by Defra (2010), while some particles can be absorbed into the tree, most are retained on the plant surface and are often re-suspended to the atmosphere, washed off by rain, or dispersed through leaf fall - consequently, vegetation is thought to be only a temporary retention site for many atmospheric particles. It is also noted that greenspace is not recommended in air quality policy as a major option for pollution reduction. This is borne out by options analysis and cost-effectiveness studies for reducing urban pollution (IGCB, 2009) – such analyses of air quality improvements options does not identify green space. Similarly, the recent Clean Air Strategy (Defra, 2019) does not identify green infrastructure as an option for England.

Climate change itself may have some impacts in altering pollution levels, notably with the potential to increase urban ozone (Hames et al., 2012; Vautard et al., 2015). The effects on PM pollution are more uncertain, and could include increases or decreases. However, these effects need to be seen in the context of air pollution policy. European air quality policy has been extremely effective in reducing air quality from historic levels and the projections from planned EU policies indicate very low levels post 2030 – therefore, the potential influence of climate change on future air quality is acting on much lower levels than today (Vautard, 2015). It is therefore extremely unlikely that climate change would drive increased demand for GI to address air quality (though there would still be air quality co-benefits from more GI).

*$CO_2$ sequestration.* There could also be increases in $CO_2$ sequestration demand to meet more ambitious greenhouse gas emissions, consistent with the UK's commitment under the Climate Act (2008). There is an extensive literature on the cost-effectiveness of options for sequestration, but again, these show that relative to conventional options, urban green space is not very cost-effective for early emission reductions (Enviros, 2006: CCC, 2012), especially at scale. It is therefore extremely unlikely that mitigation targets would drive increased demand for urban GI to reduce emissions (though there could still be GHG emission reduction co-benefits from more GI). However, it is noted that rural green space will be critical for delivering large emissions reductions, notably if the UK is to meet net zero emission (CCC, 2019). Against this background, the added contribution of urban sequestration may have a small, but useful, contribution.

**Does climate change alter the attractiveness of green infrastructure for adaptation and its uptake?**
The final aspect is whether or not climate change itself could be a driver for the greater uptake of green infrastructure as an adaptation option. This is explored in more detail in a later section.

## Step 3. What are the economic costs of climate change, i.e. the effect on the outcome?

There are potential economic costs from climate change affecting the performance of green infrastructure. This includes costs from climate extremes and damage costs (restoration and repair costs), for example the costs of restoring damage from tree falls and other material following storms (e.g. Prichard, 2012).

However, green infrastructure has a set of wider economic benefits, associated with the ecosystem services it provides (see above). Addressing question 1 above, climate change has the potential to reduce the planned function and effectiveness (benefits) of green infrastructure and therefore affect the economic benefits it provides, i.e. reducing the ecosystem services that it provides with associated economic costs. There appears to be no evidence on how large these potential effects are, but as outlined above, they are likely to be most relevant to adaptation service benefits.

In addition, climate change could also affect the costs of operating and maintaining green infrastructure, because of additional vegetative growth and thus higher maintenance costs, as well as posing risks to assets. There are studies (Hudson, 2003) that have assessed the costs of maintaining green infrastructure under a warmer climate, finding that these costs increase - though this could also provide some additional benefits, i.e. enhanced function in the form of sequestration.

The case study has investigated the baseline costs and benefits of different green infrastructure, then used this to scope out how much climate change could affect these.

Green Spaces

There are studies on the amenity benefits of urban green areas, assessing the benefits from the ecosystem services above (Cheshire et al 2002: Naidoo et al 2006), as well as recreational benefits. Two principal studies have been undertaken in England – focussing on the valuation of green infrastructure in two urban areas; Greater Manchester and Birmingham. The study for Greater Manchester (Dennis and James, 2016), assessed the value of twelve collectively managed green spaces. It values micro-climate regulation services as well as food yield, volunteer hours and therapeutic benefits. It finds a total value of £948,700/hectare/annum. This is compared with the value derived from the TEEB database (Brenner-Guillermo, 2007) of £4,617/hectare/annum, with the difference accounted for by the variation in ecosystem services considered, and the value of additional management. The study for Birmingham (Holzinger et al., 2014) provide what the authors call "best guess" estimates of the values for a range of habitats. They are presented in the table below. The table highlights that only a small range of ecosystem services have been considered, and that of those that have, valuation is rather partial. Nonetheless, it is noteworthy that the average hectarage values for the four habitats encompass the value from the TEEB study given in the Greater Manchester study. Indeed, that value, of £4,617/h/a is closely comparable with the average value in the Birmingham study, of £5,536.

**Table 2** Ecosystem values for Urban Green Infrastructure: Birmingham (£,2011).

| **Ecosystem services** | | **Woodland** | **Heathland** | **Wetland** | **Grassland** | **Total** |
|---|---|---|---|---|---|---|
| **Provisioning** | Water supply | | | 1000 | | 1000 |
| | Wild species diversity | 250,000 | 190,000 | 100,000 | 30,000 | 640,000 |
| | Recreation | 1,420,000 | 650,000 | 100,000 | 100,000 | 10,130,000 |
| **Cultural services** | Aesthetic & sense of place | 7,780,000 | | | | |
| | Cultural heritage | | | | | |
| **Regulating services** | Flood regulation | 760,000 | 100,000 | 100,000 | 10,000 | 980,000 |
| | Storm buffering | | | | | |
| | Water quality regulation | | | 80,000 | | |
| **Total** | | 10,200,000 | 940,000 | 380,000 | 140,000 | 11,660,000 |
| **Mean value/hectare** | | 6,678 | 3,034 | 1,904 | 2,005 | 5,536 |

The table shows that the dominant ecosystem service benefit is recreation (and for woodland, aesthetic benefits). As highlighted above, climate change is likely to have modest impacts on recreational services and therefore the economic costs of climate change on the outcome is likely to be modest. The main short-term effects are likely to arise from extreme events (and access to these services).

With regard to health benefits, a review of the literature conducted by Fairbrass et al (2018) for UCL found that:

- Proximity to green space could improve people's health, for example by encouraging more regular cycling and walking. It was estimated that urban parks alone annually save the national economy

£1.6m to £8.7m, including savings to the NHS of £0.3m to £1.8m. One mechanism through which this is thought to occur is the increase in physical activity associated with green space.

- In London, urban tree canopy removes between 852 and 2,121 tonnes of PM10 per annum, and increasing canopy coverage by 10% of the current GLA land area would remove 1,109-2,379 tonnes of PM10 from the atmosphere by 2050.
- Increasing green space had a protective effect for some diseases such as coronary heart disease (CHD), asthma, chronic obstructive pulmonary disease (COPD), diabetes mellitus, blood pressure, and those associated with income deprivation.
- Increasing frequency and duration of visits to green spaces reduced incidences of depression and high blood pressure, leading to the conclusion that visiting outdoor green space for at least 30 minutes a week can reduce the prevalence of depression by 7% and high blood pressure by 9%.
- Tree coverage appears to be a strong factor influencing social cohesion, and appears to facilitate reduction in crime, particularly in poor, inner-city neighborhoods.

The economic benefits of air quality reductions can be quantified, using Defra Damage cost values (Defra, 2019). These would indicate high economic benefits even from modest air pollution reduction, because these are removed in urban areas (e.g. £tens of millions/annum), but this is for the large areas of existing green space (e.g. in London): the marginal reduction (for new green areas) would be modest.

There are economic benefits from urban $CO_2$ sequestration. In terms of national emissions, these sequestrations are low (BEIS, 2016). Further, new urban greenspace has limited potential for large GHG sequestration, compared to other mitigation options, because it is difficult to achieve reductions at scale (see earlier discussion). However, climate change has the potential to increase the relative sequestration levels of existing and new green space, from longer growing seasons and enhanced $CO_2$ fertilisation effects (Hudson, 2003). This would be expected to enhance sequestration benefits. However, some of these benefits could be offset from changes in suitability (reduced growth outside suitability tolerances) and extremes (from damage to GI).

Urban greening has the potential to decrease the UHI impact and building overheating, which may also lead to health co-benefits. These are discussed in the adaptation discussion later.

There may also be economic co-benefits from GI. Fairbrass et al. relates to the possible social impact of GI through increasing house prices. For example, from 2003 to 2011, property prices surrounding the New York High Line rose by 103%. This may mean that local residents in vulnerable populations are displaced to less desirable locations in order to find affordable housing.

There is some evidence on the potential increased maintenance costs of green infrastructure under climate change. This relates to the fact that some plants used in GI – including, e.g. grass maintained in park-lands – are likely to have longer growing seasons in England under climate change scenarios and therefore require more maintenance expenditure on grass cutting, etc. As an indication of the possible extent of this, Hudson, (2003), models the effect of climate change scenarios on the 30 acres of formal gardens of Lanhydrock House and Gardens, which is the most visited National Trust property in Cornwall. The study found that average annual climate change-induced maintenance costs at Lanhydrock to 2100 are between £2,600 and £8,000 (undiscounted) for low and high scenarios, respectively. These represent broadly 20% and 70% increases on current annual lawn maintenance costs. From 2020 to 2050, this equates to a range of £80,000 to £120,000.

Green roofs

Mayer et al., (2015) summarizes the costs and benefits from the literature regarding green roof installations (see also final section below). This study reports that the largest economic benefits are from energy demand reduction for indoor heating. These benefits are projected to decrease with climate change, because there are projected lower heating degree days (and heating demand) under climate change (CCC, 2014).

SuDS

Ossa-Moreno et al. (2017) assessed the economic benefits and costs of SuDS (see later section), assessing the primary function (flood management) and the co-benefits that include amenity, air quality enhancements, biodiversity and ecology, and health improvements. Climate change will potentially increase the flood control potential of SuDS, but there may be limits to the potential for more extreme events (Dadson et al. 2017). The potential benefits or co-benefits will be similar to the discussion above for green space.

**Change in demand (for non-climate ecosystem services).**

It is more difficult to estimate how much climate change might affect the demand for broader ecosystem services associated with GI, and how this translates into additional GI demand, but we hypothesise it might increase recreational demand, and $CO_2$ sequestration, but not make much difference to air quality. The hypothesis that there could be an increased demand for recreational possibilities in cities that would use green infrastructure is supported by McEvoy et al (2005) who suggest for Manchester that warmer weather is likely to increase demand for access to public space and could help boost the café culture. However, this study also highlights the risk that with temperatures disproportionately high in the city centre during hot spells, there is the possibility that residents and visitors will opt to leave the city centre.

## Step 4. What are the potential additional adaptations options to address impacts?

For question 1) above, the issue is what additional adaptation can be taken to make sure green infrastructure is climate resilient (to the future impacts of climate change), i.e. addressing the impacts on various ecosystem services, i.e. on amenity and recreation, health benefits, etc.

For question 2) above, the issue is on the role of green infrastructure as an adaptation option in its own right (ecosystem-based adaptation). This requires an analysis of relative attractiveness of green infrastructure options (as an adaptation option), but also other adaptation actions that are needed to incentivise/address barriers to GI, to enable uptake.

**1) Options to make green infrastructure more climate resilient**

The first set of additional options are to consider additional options to make green infrastructure climate smart (to future climate change) to ensure the increase in GI delivers its anticipated benefits (as set out in the 25YEP).

There are various options to make green infrastructure climate smart. For example, choosing more resilient species for urban green areas, making green roofs drought-resistant or sustainable urban drainage (SuDS) able to cope with increased heavy precipitations/peak flows.

Green areas

Climate change is going to increase the risk of urban heat spikes, and surface water flooding due to more frequent and intense rainfall, and could change patterns of average rainfall and dry spell duration/drought. There are also risks in terms of windstorm damage. There is a well-established literature on the climate resilience for forestry, which while focused on commercial species, has high relevance for urban trees. This includes the choice of variety and also management practice (e.g. see Frontier Economics et al., 2013). Information is also provided in the existing forestry adaptation literature. (Forestry Commission, Defra Tree Health Resilience Strategy (Defra, 2018c))

There are also issues on green space design, and the need to ensure sufficient capacity for heavier precipitation and changes in possible flood risks. Information is also available from the Forestry Commission's ecological site classification tool.

### Green roofs

Similarly, there are potential issues for green roofs and walls, with the potential to consider the choice of varieties and species, as well as management practice and design. It is highlighted that the plant species used for green roofs tend to have shorter life-times, so there is less issue of lock-in, but over time there will still need to be the consideration of planting that enhances resilience to heat and dry spell duration.

### SuDS

Sustainable urban drainage (SuDS) techniques would need to account for the potential for increasing flows under future climate scenarios. This might involve greater area (to allow adequate drainage) as well as greater provision to cope with extreme heat and dry spells.

## 2) Green infrastructure as an adaptation option

The second set of options assesses the role of green infrastructure as an urban adaptation option. In this case, climate change may incentivise the uptake of GI, due to increased demand for urban adaptation, however, the role of green infrastructure for adaptation without regulation will depend on its relative performance over grey adaptation infrastructure.

The effects of climate change on adaptation function are likely to vary with GI type. Rising urban heat is likely to incentivise the uptake of some forms of GI, although the level of implementation will depend on the relative costs and benefits compared to other alternatives (see later). Increasing heavy precipitation may increase the demand for urban flood management, but there are some studies that highlight the limits of natural flood management (Dadson et al, 2017), i.e. it is unclear if a changing climate will increase or decrease the attractiveness of these options. There is also likely to be a difference by scenario (2 vs 4°C, or the range between the 10th and 90th percentiles for a particular emissions pathway). Under warmer scenarios (e.g. 4°C), there is likely to be increased demand for heat reduction (CCC, 2012), which in turn could increase demand for GI.

### Urban green spaces and integrated green infrastructure

There are a large number of possible green space adaptation measures (Loibl et al, 2016). These may include greening streets (shade trees), converting paved places into green ones, reducing sealed surfaces, planting trees, shrubs and grass to establishing new neighbourhood parks. This includes the potential for retrofitting of green space into existing areas, their inclusion in refurbishment of areas or building, or new green spaces. It can also include activities to increase the adaptation functionality in existing green spaces (i.e. more explicit focus on the types of green that enhance cooling, or are more targeted at drought management planning), rather than maximising for recreational benefits.

Different schemes achieve different levels of reduction in the urban heat island effect, or local thermal comfort (indoors and outdoors). These benefits may arise from a set of reasons, such as direct shading, enhancing wind and aiding circulation, reducing irradiance and supporting nocturnal energy flux with the atmosphere. There is some literature on the potential benefits of green space for cooling.

Bowler et al. (2010) used meta-analysis to synthesize data on the cooling effect of parks. Their results show that, on average, a park was 0.94°C cooler in the day. Studies on multiple parks suggest that larger parks and those with trees could be cooler during the day. However, the authors also highlighted that that evidence for the cooling effect of green space is mostly based on observational studies of small numbers of green sites. The impact of specific greening interventions on the wider urban area, and whether the effects are due to greening alone, has yet to be demonstrated.

As highlighted above, Gill et al (2007), using Greater Manchester as a case study, found that if green cover in high-density residential areas and town centres was reduced by 10 per cent, surface temperatures are projected to be 7°C or 8.2°C warmer by the 2080s High emissions scenario in each, when compared to the 1961–1990 baseline case; or 3.3°C and 3.9°C when compared to the 2080s High emissions case where green cover stays the same. The converse would mean that increases in green space would lead to major cooling benefits. However, the size of these changes is extremely large and involves extremely high land-use values (Greater Manchester includes 10 large boroughs and is 1,277 km$^2$, so 10% would be an extremely large area of land with an extremely high land value).

Kingsborough et al. (2017) tried to estimate the impact of GI on reducing the risk of heat-related deaths. They found that city-scale urban greening has the potential to decrease the UHI impact. Increasing London’s urban green space by 50% is projected to reduce future summer Tmax by 0.28C. In the 2080s this corresponds to 49 fewer heat-related deaths each year compared to a no-adaptation scenario. Alternatively, decreasing London’s green space by 25% by the 2080s is projected to increase summer Tmax by 0.17°C, which corresponds to 26 more heat-related deaths per year compared to a scenario where existing levels of urban greening are maintained, as Figure below. These additional deaths can be expressed in monetary terms if we apply a Value of a Prevented Fatality (VPF). The VPF most commonly used in England is that estimated by the Department for Transport (DfT) and therefore regarded as the default value to be used by other parts of Government. The value of £1,554,395 for a VPF is to be found in the TAG book (DfT, 2018). The annual total is then £40.4 million, which – as an upper bound to 2050 - equates to £1.2 billion for the period, 2020-2050. It is noted that these results focus on the impacts of green infrastructure on the urban heat island effect and do not reflect localised impacts such as shading of buildings, or the enhanced insulation provided by green roofs. Nor do they seek to quantify other impacts of urban greening such as storm water attenuation.

The findings of this study suggest that failing to invest in GI could indeed increase the risk of heat-related deaths under future climate scenarios. However, the authors found that although urban greening has a positive impact on reducing heat-risk compared to the no-adaptation scenario, it would not reduce the UHI enough to wholly offset the impacts of climate change even under the extremely optimistic uptake scenario.

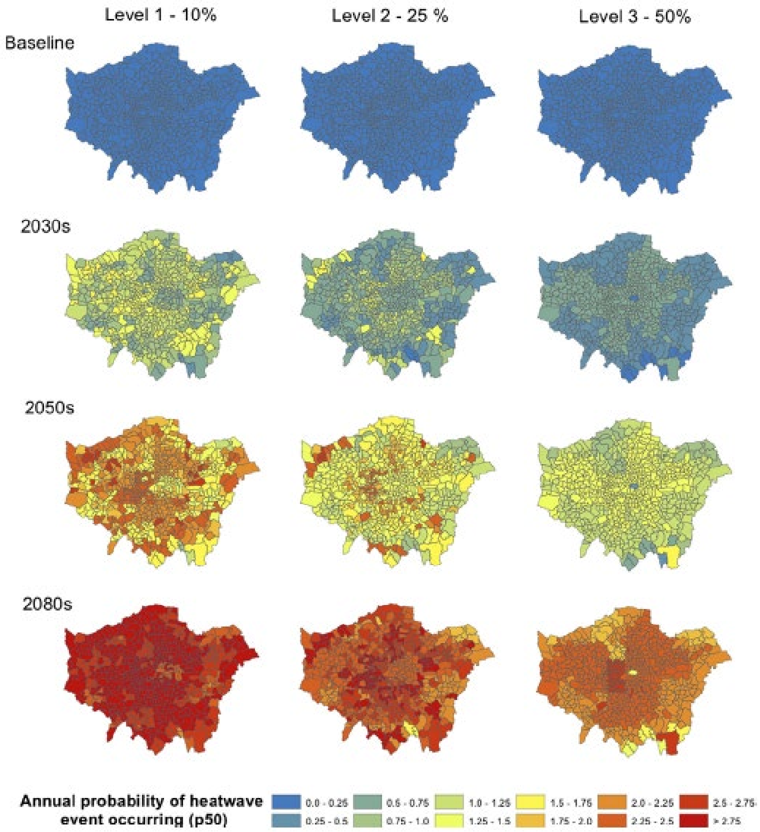


Figure 4 Level 1–3 residential overheating risk: no-adaptation.

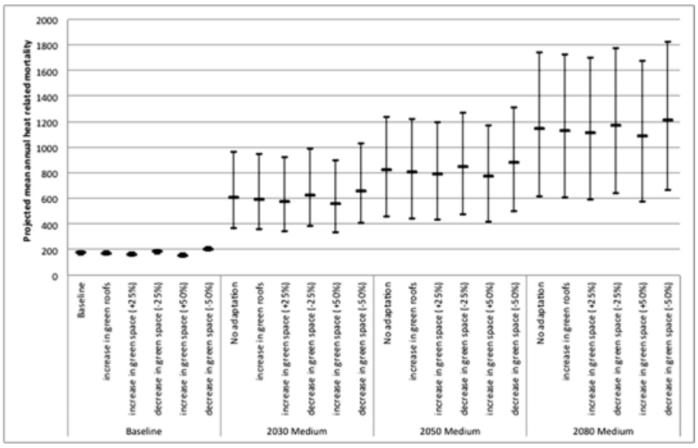
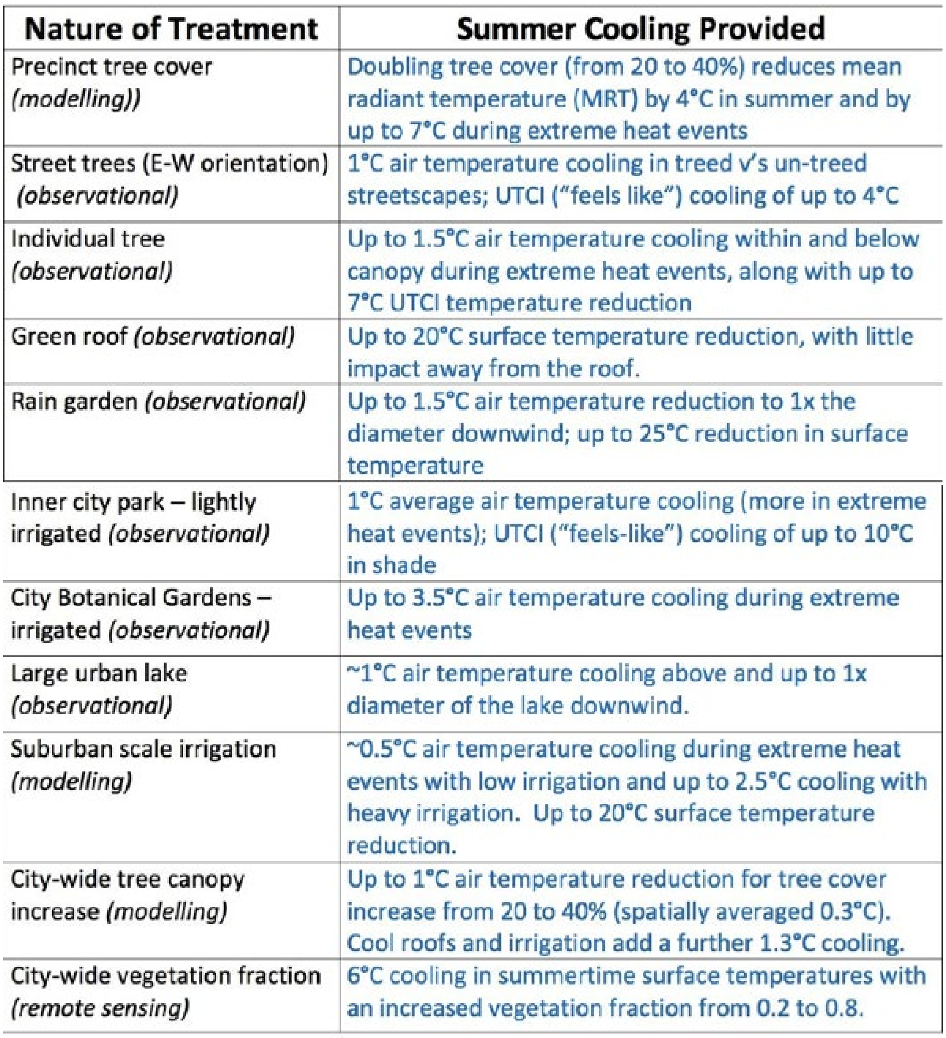


Figure 5 Estimated annual heat-related mortalities for urban greening scenarios (p10 and p90 are lower and upper bounds).

Demuzere et al. (2014) report that studies of parks in Singapore showed that the temperature outside the park's boundary gradually increases when moving further away from the green area. The cooling impact of parks is also reflected in the lower temperatures in the surrounding built environment (the maximal average temperature difference in locations nearby the park: 1.3 °C). A simulation of a cooling energy load in surrounding buildings showed a maximum 10% reduction of energy consumption. Similarly, a study in Tel Aviv predicted the cooling effects of small urban green wooded sites to be about 2.8 °C; while in Japan the accelerated temperature increase of 0.16 °C/year was linked to the decrease of vegetated area in a low populated urban sprawl.

Tapper (2019) from Monash University presents a review of the literature around the impacts of different measures on cooling (below) based on a series of studies (Coutts et al., 2013: Coutts et al., 2016a: Coutts et al., 2016b; Thom et al., 2016.

Table 3 UHI Cooling effects of Alternative GI measures. Source Tapper, 2019.



| Nature of Treatment | Summer Cooling Provided |
|---|---|
| Precinct tree cover *(modelling))* | Doubling tree cover (from 20 to 40%) reduces mean radiant temperature (MRT) by 4°C in summer and by up to 7°C during extreme heat events |
| Street trees (E-W orientation) *(observational)* | 1°C air temperature cooling in treed v's un-treed streetscapes; UTCI ("feels like") cooling of up to 4°C |
| Individual tree *(observational)* | Up to 1.5°C air temperature cooling within and below canopy during extreme heat events, along with up to 7°C UTCI temperature reduction |
| Green roof *(observational)* | Up to 20°C surface temperature reduction, with little impact away from the roof. |
| Rain garden *(observational)* | Up to 1.5°C air temperature reduction to 1x the diameter downwind; up to 25°C reduction in surface temperature |
| Inner city park – lightly irrigated *(observational)* | 1°C average air temperature cooling (more in extreme heat events); UTCI ("feels-like") cooling of up to 10°C in shade |
| City Botanical Gardens – irrigated *(observational)* | Up to 3.5°C air temperature cooling during extreme heat events |
| Large urban lake *(observational)* | ~1°C air temperature cooling above and up to 1x diameter of the lake downwind. |
| Suburban scale irrigation *(modelling)* | ~0.5°C air temperature cooling during extreme heat events with low irrigation and up to 2.5°C cooling with heavy irrigation. Up to 20°C surface temperature reduction. |
| City-wide tree canopy increase *(modelling)* | Up to 1°C air temperature reduction for tree cover increase from 20 to 40% (spatially averaged 0.3°C). Cool roofs and irrigation add a further 1.3°C cooling. |
| City-wide vegetation fraction *(remote sensing)* | 6°C cooling in summertime surface temperatures with an increased vegetation fraction from 0.2 to 0.8. |

One caveat to the potential of green cover in moderating surface temperatures is the case of drought, when grass dries out and loses its evaporative cooling function. In other words, climate plays a very important role on the mitigation potential of cool and green roofs and other GI. For example, in sunny and dry climates, reflective roofs present an important advantage while in moderate and cold climates vegetative roofs seem to present higher benefits (Satamouris, 2014).

Similarly, Filho et al (2018) speculate that urban streams and lakes have the potential to cool urban areas, but the mechanisms are not direct, and some studies have suggested that water bodies can actually maintain or increase temperatures at some times during the day. At the same time, water features can be prone to drought, which is likely to be when they are most needed. However, as with urban greening, water features provide a range of other benefits, such as amenity, and if designed as part of a wider strategy might provide flood mitigation or other benefits (Coutts et al., 2013b, 2014 in Filho et al. 2018).

Trade-offs also exist, for example with water usage: unless adequate provision is made there could be conflict as greenspace might require irrigating at the same time as water supplies are low and restrictions may be placed on its use. Similarly, planting trees too close to houses can increase the risk of subsidence.

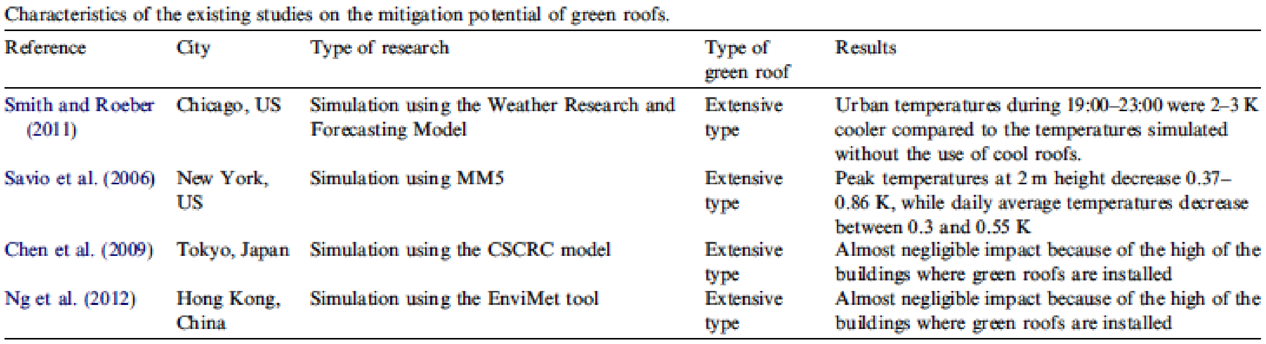
At the smaller scale, a case study of a 2500 $m_2$ neighbourhood garden in central Lisbon, microclimate data were recorded both within and beyond the garden during hot summer days. Temperatures within the garden were often significantly cooler than nearby locations. The local cooling effect on the hottest day achieves a temperature reduction of 6.9 °C against the surrounding built up area (Oliveira et al, 2011). The study demonstrates that the cooling effect of small green spaces in cities may also extend for some distance beyond the green areas – 200 metres in this study.

Green Roofs

There is some literature on the effectiveness of green roofs for cooling. These involves studies that look at the cooling benefit within buildings as well as the ambient (outdoor) cooling effects, noting these are very different.

There are some studies that report very high cooling benefits (Coutts et al, 2013), but these tend to be for houses designed for maximum cooling in hot locations. In the UK the main benefits – and thus design – have to date been around reducing heating demand.

Satamouris (2014) highlighted that only a few studies aiming to evaluate the heat island mitigation potential of green roofs on a city scale are available. Most of the studies use simulation techniques based mainly on mesoscale models, and consider roofs of extensive type. Studies are available for New York and Chicago in US as well as for Hong Kong and Tokyo. Results are reported in the table below. Interestingly, as the author reports, one study in Hong Kong (Ng et al. 2012) found that the possible decrease of the ambient temperature due to green roofs at street level in high-rise high-density area is almost zero. The study concludes that when the building height to street width (aspect), ratio exceeds 1 (one), the possible cooling benefits at grade is low. However, it is stressed that these simulations usually assume very high levels of uptake for green roofs, and there is a question of how realistic high uptake scenarios are, because of barriers to uptake.



Characteristics of the existing studies on the mitigation potential of green roofs.

| Reference | City | Type of research | Type of green roof | Results |
|---|---|---|---|---|
| Smith and Roeber (2011) | Chicago, US | Simulation using the Weather Research and Forecasting Model | Extensive type | Urban temperatures during 19:00–23:00 were 2–3 K cooler compared to the temperatures simulated without the use of cool roofs. |
| Savio et al. (2006) | New York, US | Simulation using MM5 | Extensive type | Peak temperatures at 2 m height decrease 0.37–0.86 K, while daily average temperatures decrease between 0.3 and 0.55 K |
| Chen et al. (2009) | Tokyo, Japan | Simulation using the CSCRC model | Extensive type | Almost negligible impact because of the high of the buildings where green roofs are installed |
| Ng et al. (2012) | Hong Kong, China | Simulation using the EnviMet tool | Extensive type | Almost negligible impact because of the high of the buildings where green roofs are installed |

*Source: Satamouris 2014.*

An EU funded project (BASE) lead by Meyers et al (2015) found conflicting results with regard to green roofs as a cost-effective adaptation measure to reduce heat stress. In the city of Jena (Germany) this measure turns out to be effective. However, this result was not confirmed by the assessments in the Madrid case study, where green roof solutions were found to be ineffective. The main reason for the poor performance of green roofs in the Iberian case studies are the substantially higher costs of this adaptation measure compared to Germany. These differences are explained by the authors by the different levels of development of market for specific adaptation technology. For Madrid it is concluded that the urban heat island effect could be reduced more effectively by tackling its causes, e.g. by reducing the use of air conditioning, than by using engineering solutions like green roofs. In the Jena case study, the use of large trees and light-coloured pavements prove to be very beneficial not only for the site-specific micro-climate but also for other aspects as the amenity value of public spaces.

*Water runoff management*

Surface water flooding is also likely to increase, particularly in urban areas. For example, parts of London are at high risk of surface water flooding, which occurs when rain falls faster than it can drain away or soak into the ground. Surface water flooding can occur very quickly in heavy storm events without adequate drainage or space for water to flow in to, leading to flash flooding. UKCP18 indicates that winter precipitation are likely to increase by approximately 10% above current levels by 2050, and up to 25% by 2100 under more pessimistic climate scenarios (RCP 8.5). Climate change, coupled with population growth could increase stress on local water resources and the volume of wastewater flowing through the sewers. Construction of new homes, schools and infrastructure could add further pressure on the drainage system by reducing permeable surfaces and increasing the volume of stormwater runoffs.

Gill et al. (2007) found that green space on its own is less effective at moderating the volume of surface runoff under climate change in Manchester. While green space helps to reduce surface runoff, especially at a local level, the increase in winter precipitation brought by climate change is such that runoff increases regardless of changes to surface cover. Thus, in order to adapt to the increased winter precipitation expected with climate change, green space provision would need to be considered alongside increased storage. There is significant potential to utilize sustainable urban drainage (SuDS) techniques, such as creating swales, infiltration, and retention ponds in parks.

Several urban green infrastructure measures (green spaces, green roofs) are also reported to reduce floods, but McVittae et al (2017) highlight that many of these measures are typically designed to mitigate 1 in 30 year flood events, and as return period (severity) increases up to 1 in 100 they are likely to be less effective in mitigating the flood entirely.

The EU BASE project led by Meyers et al. (2015) found that when comparing different measures for flood retention, the more structural solutions such as green roofs or rainwater harvesting turn out to be much more expensive than green measures such as green corridors and rivers rehabilitation. In the case study in Leeds the greener measures, i.e. Sustainable urban Drainage Systems (SuDS) and Ecosystem-based Adaptation (EBA), were more expensive than grey infrastructure, although the former provide a multitude of co-benefits not provided by the grey infrastructure measures.

A report by Defra (2013) prepared by Frontier Economics and partners investigated the benefits of Natural Flood management solutions. (Figure 6 below). It finds that the need for flood risk management and the extent to which NFM options would be effective depend on the localised factors of each river catchment, and the evidence around their effectiveness is uncertain.

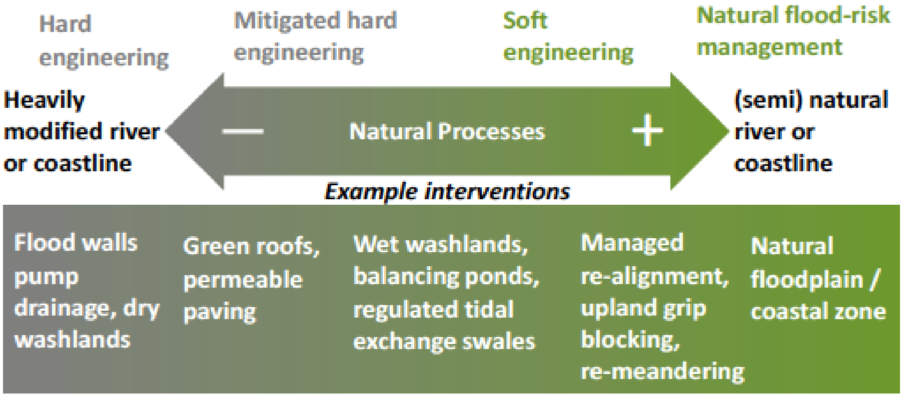


Figure 6 Examples of Natural Flood Management schemes

*Source: Defra (2013)*

Defra (2013) concluded that although a number of research projects commissioned by Defra, the EA and others support a view that NFM techniques applied at the local scale can deliver measurable benefits (table below), the complexity of the systems involved that the extent to which this approach can be scaled-up is less certain. The evidence is limited, and where data have been collected, a long time-series does not exist. Further, where poorly designed and/or implemented, NFM can increase flood risks both upstream and downstream. For instance, incorrect riparian woodland placement can increase risk for upstream communities. The authors also stressed that trade-offs should also be considered. For example, measures to increase responses to flooding can reduce water availability. For instance, increased tree cover can increase evapo-transpiration and reduce soil moisture content. Similarly, maintaining water storage bodies at low levels before winter to accommodate potentially higher winter rainfall, may lead to water shortages in the subsequent year.

Dadson et al (2017) highlights that urban flooding is generally greatest from intense convective storms in summer. They highlight that engineering interventions, including permeable paving, stormwater retention and storage basins and sustainable drainage systems (SuDS), can avoid, mitigate or even reverse the adverse effects of urbanization on surface run-off. They also highlight that restoration of urban watercourses and their vegetated riparian corridors, plus reconnection of their floodplains can be used to convey or store urban run-off while encouraging infiltration and improving water quality.

There has also been some recent work on looking at adaptation pathways for SuDS (Kapetas and Fenner, 2019).

**Mapping green infrastructure to the early priorities for adaptation.**
The study has also considered how GI aligns to the three early priorities for adaptation.

- No and low-regret. Green infrastructure has most potential as a win-win option, due to the co-benefits it involves.
- Early decisions with a long life-time. There is a good argument for making new green infrastructure climate resilient, noting this would be easier if considered during design, noting that it may have greater flexibility than grey, but also that it might not (on its own) provide sufficiently high levels of resilience to reduce impacts to zero.
- Early preparation for long-term climate change. Urban heat in major cities in England is likely to be a major future issue, and there is a very strong case for enhancing the analysis, research and monitoring of urban green space and UHI, and using information to feed back into policy.

**Barriers to green infrastructure**

The low uptake of green infrastructure can be explained by several barriers which limit uptake. Byrne and Yang (2009) identified four classes of interrelated factors that shape the efficacy of green-space: the biophysical character of the built environment; planning systems; institutional frameworks and governance structures; and the perceptions and values of urban residents. Further barriers include the lack of strong quantitative evidence regarding their benefits, and the poor replicability of the empirical results of different studies. Demuzere et al. (2014) found that despite an increasing body of knowledge related to the estimation of the benefits provided by green urban infrastructure, it remained difficult to draw unambiguous conclusions regarding their actual contribution. The main reason was whether the evidence obtained in specific conditions could be reproduced in other conditions and spheres. This 'information failure' makes the work of urban planners more challenging, and hinders GI uptake. However, a more detailed look at the results – shown below – shows that the highest barrier in terms of information are for air quality and heat – there was much stronger evidence of the health and $CO_2$ benefits, as well as flood management benefits.

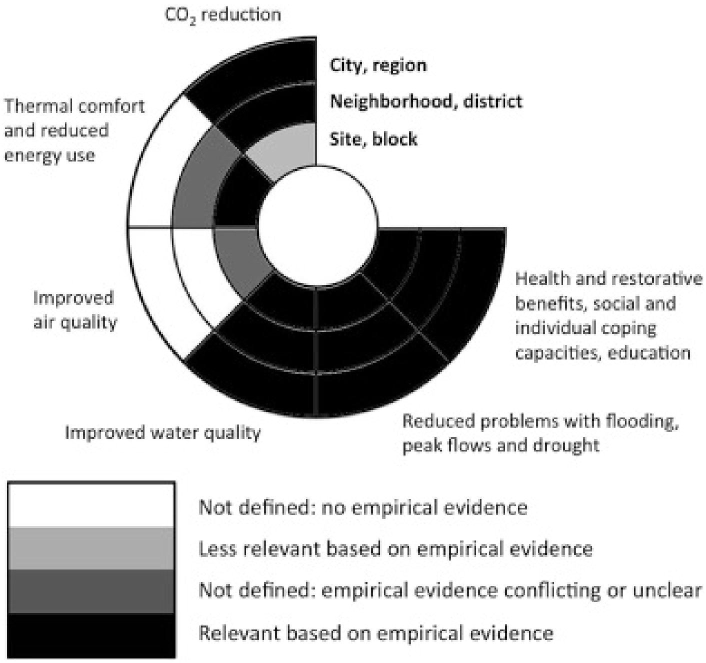


Figure 7: Relevance of the benefits from green urban infrastructure for climate change adaptation and mitigation on three spatial scales, based on the evidence  Source: Demuzere et al. 2014

Path dependency is also an institutional barrier, as identified by Byrne and Yang (2009). This refers to situations where institutions become accustomed to certain issues and activities over time, and consequently become reluctant to respond to the emergence of new imperatives. Spatial planning regimes are vulnerable to path dependence and may resist change, including the need to respond to climate change. A key challenge for planners is how to use green infrastructure as a new and innovative form of planning, not just re-branding existing initiatives as somehow being 'green' (Matthews, 2015).

There are some physical barriers, notably because in many existing urban areas, it is not feasible to create large new greenspaces. Thus, greenspace would have to be added creatively by making the most of all opportunities, for example greening of roofs, building façades, street tree planting, etc. There is some evidence that the green infrastructure literature has somewhat overlooked the existence of path dependence as a barrier to institutional change (Matthews, 2015). Opportunities to enhance green cover should also be taken when structural change is taking place, for example, in urban regeneration projects and new development (Gill et al. 2007).

Finally, a set of critical barriers exist around the financial and economic barriers. The first is financial, represented by the opportunity cost of land. There is large land-use pressure in urban developments to accommodate increasing population. Accommodating this growth could require extensive development. This means that land-use prices, which are already high, could continue to increase. Diverting land that could be developed to green spaces, therefore has a very high opportunity cost[2]. For major urban areas, these costs are often prohibitive, and provision of GI is unlikely to happen autonomously due to the opportunity cost to developers.

There are economic studies that compare the costs and benefits of green infrastructure to grey alternatives. This is discussed more below, but in summary, there is a large range of capital costs for GI. Some schemes have lower capital costs (especially then heavily engineered options) but for some area-based schemes, land-prices (opportunity costs) are very high.  Moreover, GI is often (but not always) more expensive in terms of management and maintenance costs. The balance of costs and benefits is therefore very influenced by the discount rate.

Ecofys (2016) identify a set of common set of factors contributing to successful implementation across all EbA categories:

**Success factors**

- Stakeholder engagement and attitudes
- Cooperation across stakeholders
- Alignment or of activities across agencies including shared institutional structures
- Existing knowledge and/or ongoing research and monitoring
- Demonstration of private benefits
- Demonstration of multiple co-benefits
- Availability of finance
- Multiple sources of finance linked to multiple benefits

**Limiting factors**

- Lack of finance for measure implementation or land acquisition/compensation
- Poor stakeholder engagement and negative attitudes
- Cooperation and consent across multiple landowners
- Lack of land or space constraints for implementation
- Time lags in observing benefits

Ecofys report a key innovative approach to success was the integration of agencies, stakeholders and their activities; the identification of multiple ecosystem service co-benefits that can be linked a variety of funding sources. This latter point reflects the fact that single benefits may not meet funding criteria. Bodies that are independent from stakeholders and agencies can also help to steer projects, bridging gaps and creating trust between different groups.

## Step 5. What are the benefits and potential costs of adaptation?

The final section looks at the potential costs and benefits of adaptation.

1) CBA of options to make green infrastructure climate resilient
There is very little information to inform the potential cost-benefit analysis of climate-smarting green infrastructure. There is information on commercial tree species choice under climate change, that could be applicable to urban greening.

2) CBA of Green infrastructure as an adaptation option

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[2] As an anecdotal example, the real estate value of Central Park has been estimated at half a trillion dollars (2005 prices), Wikipedia.

The case study has reviewed the literature on costs and benefits of green infrastructure as an adaptation option. This is generally focused on the additional benefits that these options may provide in a changing climate, with the comparison of how these compare to conventional options to address increases in heat or flooding.

### Green areas

Findings in the literature are mixed. Liu et al. (2016) conducted a cost-benefit analysis to assess four designed green infrastructure options: green space depression, porous brick pavement, storage pond, and their combination. They found that an average ratio of annual benefits to costs of the four green infrastructure options was 1.9:1. Physically integrated options had the highest economic feasibility with a benefit to cost ratio of 2.2:1, followed by the storage pond construction with a benefit to cost ratio of 2.1:1. The results suggested that whilst the storm-water reduction and utilization by green infrastructures had higher construction and maintenance costs, their comprehensive benefits including source water replacement benefits and other environmental benefits are potentially dominant. Mendizabal and Peña (2017), found positive BCRs for planting extra trees in urban areas, and greening urban spaces of 2.1:1 and 1.5:1 respectively. However, a study in Austria (Loibl et al, 2016) that assessed the potential UHI mitigation effect from increasing the park area found that this was an economically inefficient option. The study assumes an expansion of the park and green areas as well as an increase of the number of trees in public spaces (streets, places, parking lots etc.). However, the study concluded large increases in these were unrealistic options due to space availability and land costs.

### Green roofs

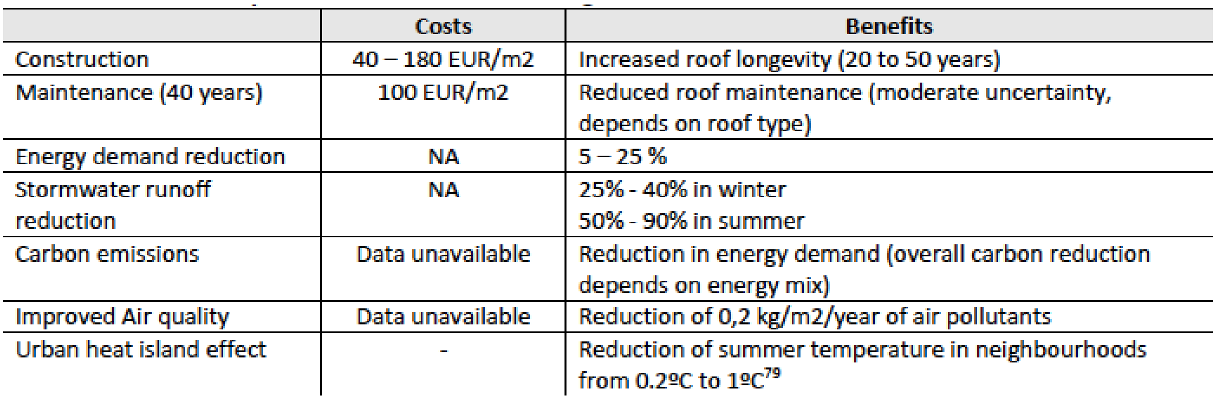
There have also been a number of studies on green roofs (van Ierland et al., 2006 in the Netherlands, LCCP 2009 in London, UBA, 2012 in Düsseldorf, and Nurmi et al. (2013) in Finland), which have been assessed in terms of co-benefits (e.g. reduced energy, stormwater management, sewer overflow, air quality, urban heat island, greenhouse gases). These show modestly favourable benefit - cost ratios, though are crucially dependent on the discount rate used, but have relatively high costs in absolute terms. Mahdiyar et al (2016) highlights that green roofs are classified as intensive or extensive according to their purpose and characteristics. Intensive roofs are associated with roof gardens; need a reasonable depth of soil and require constant maintenance. Extensive roofs have a relatively thin layer of soil, and are designed to be virtually self-sustaining, therefore require low maintenance. Installation cost, maintenance, and construction time depend on the type of the green roof. Compared to the intensive type, extensive green roofs are lighter and require lower maintenance cost. However, other benefits such as retention and delay of storm water, temperature control, and agricultural space effects are also likely to be lower.

Clark et al. (2008) showed that Net Present Value (NPV) for a conventional roof is between 20% and 25% more than an extensive green roof during its lifespan. Carter and Keeler (2008) found that extensive green roofs are more expensive than conventional ones, with additional costs ranging from 10% to 14%. They therefore concluded that a 20% reduction in initial cost is necessary to consider this type of green roof as an economically feasible construction practice. Bianchini and Hewage (2012) assessed the costs and benefits involved in installing green roofs. The results from their study indicate that by installing any type of green roof the typical payback period if only private cost and benefits are considered is 6 years for intensive green roofs and around 4.6 years for extensive green roofs, and shortens to around 5.7 years and 4 years, respectively, once social costs are incorporated.

McVittie et al (2017) reviewed case studies of existing green roofs, finding the cost estimates for green roofs are highly variable ranging from €8 to €90 per m$^2$. These costs may be offset by private benefits including reduced cooling and heating costs, the savings being up to €8.5/m$^2$ and €24/m$^2$ respectively (based on Urban green roofs in Helsinki).

A further study, (Mayer et al., 2015) summarizes the costs and benefits from the literature regarding green roof installations. Note that in the results shown in Table 4 benefits are expressed in physical rather than monetary metrics, reflecting the challenge of monetisation in this decision context.

Table 4 Meta-Analysis of Green roof cost-benefit analysis.



| | Costs | Benefits |
|---|---|---|
| Construction | 40 – 180 EUR/m2 | Increased roof longevity (20 to 50 years) |
| Maintenance (40 years) | 100 EUR/m2 | Reduced roof maintenance (moderate uncertainty, depends on roof type) |
| Energy demand reduction | NA | 5 – 25 % |
| Stormwater runoff reduction | NA | 25% - 40% in winter<br>50% - 90% in summer |
| Carbon emissions | Data unavailable | Reduction in energy demand (overall carbon reduction depends on energy mix) |
| Improved Air quality | Data unavailable | Reduction of 0,2 kg/m2/year of air pollutants |
| Urban heat island effect | - | Reduction of summer temperature in neighbourhoods from 0.2ºC to 1ºC[79] |

*Source: Mayer et al. (2015)*

Flood control and SuDS

There are several studies on SuDS. The most relevant includes Ossa-Moreno et al. (2017) which undertakes cost-benefit analyses of five catchment-wide SuDS schemes in the Decoy Brook catchment in London, UK. The five schemes are comprised of:

1. Infiltration strips along the main roads of the catchment (A502and A598), an urban wetland to the south west corner and a rainwater tank for Golders green station.
2. A 7500 m3basin at Hampstead Heath Extension (east basin) and a 1000 m3basin at Princess Park (west basin).
3. Infiltration strips and roof disconnection in the Police Station Sub-catchment, and a swale to the north of the catchment.
4. Combination of options 1 and 2.
5. Combination of options 2 and 3.

The study is unique in quantifying the non-financial benefits of SuDS. The Benefit of SuDS Tool (BeST) developed by the UK Construction Industry Research and Information Association was used to appraise these benefits that include amenity, air quality enhancements, biodiversity and ecology, and health improvements. The analysis split benefits between private benefits derived from avoidance of damage to property and its contents, and the non-financial benefits of the type listed above. Summary results are presented in Table 5. They serve to demonstrate the importance of considering wider benefits when considering the economic rationale for SuDS schemes.

Table 5 Net Present Values (NPV) and Benefit-Cost Ratios of SuDS schemes in North London

| | Private Benefits | | Private & Wider benefits | |
|---|---|---|---|---|
| | NPV | B-C Ratio | NPV | B-C Ratio |
| SUDS 1 | -£363,079 | 0.32 | -£62,737 | 0.91 |
| SUDS 2 | -£169,869 | 0.66 | £10,385 | 1.06 |
| SUDS 3 | -£199,729 | 0.64 | £390,960 | 1.82 |
| SUDS 4 | -£532,948 | 0.47 | £62,741 | 0.97 |
| SUDS 5 | -£369,598 | 0.65 | £401,345 | 1.46 |

There are some further cost-benefit studies on natural flood management, though much of these are focused on the alternative to grey infrastructure for flood management more generally, rather than specifically on urban areas.

For coastal areas, De Bruin (2012) looked at sea level rise in the Netherlands and compared a non-technical option (sand dunes) against hard structural protection: while the soft schemes offered greater flexibility and lower capital costs, maintenance costs were higher, thus ranking of schemes is influenced by discount rate. There are cost-benefit studies of salt marshes in the Netherlands (Rijkswaterstaat Waterdienst, 2011) which reports these eco-variants are less expensive than traditional options over the longer term (net present value) and in terms of construction costs, but they are more expensive in terms of management and maintenance costs alone. There are studies that appraise alternative flood management strategies, such as recent analysis in New York (Aerts et al., 2013: Aerts et al., 2014), which compared the costs of large-scale flood protection, wetland restoration and buffer zones and increased building codes for future climate change as well as other long-term challenges. The initial investment costs of alternative strategies varied between $11.6 and $23.8 billion, maximally, though a hybrid solution, combining protection of critical infrastructure and resilience measures that can be upgraded over time, was found to be less expensive. However, with increasing risk in the future, storm surge barriers may become cost-effective, as they can provide protection to the largest areas in both New York and New Jersey.

Similar studies exist for river flooding. This include watershed management (enhanced conservation and restoration, notably of upstream catchments with forests), natural flood plain management, including water flow regulation and controlled flooding, natural protection structures (e.g. as an alternative to concrete), and sustainable urban water management (i.e. urban drainage) to reduce urban flood risks. It also includes spatial options that move beyond engineered control, such as the ‘room for the river’ strategy in the Netherlands. There has been a review of green schemes in Europe (HKV and RPA, 2014), where they are a priority in European adaptation policy. This identifies some cost-benefit studies of existing ecosystem based (green) schemes. In the Netherlands (Rijkswaterstaat Waterdienst, 2011) considered 2 freshwater sites and found ecological variants of flood defences (e.g. reed-land) were less expensive over the longer term (net present value) and in terms of construction costs, but more expensive in terms of management and maintenance costs alone. There are also assessments of wetland restoration in Stockholm (Kettunen, 2011), flood storage in the Humber estuary in the UK, with benefits in avoiding upstream defences (EA, 2009c) and for the Elba in Germany (Teichmann and Berghöfer, 2010: TEEB DE 2014). Economic analysis on these options - in the context of climate change - was also undertaken in the UK (Frontier, 2013b). However, it is worth noting that benefits are often delivered in the future, due to the time for full ecosystem establishment and services (Naumann et al., 2011).

Conclusions

There are recognised to be climate change risks to green infrastructure in urban areas; it is also reasonably well-established that green infrastructure offers adaptation options to climate change risks such as urban heat island effects as well as urban drainage flooding. However, the evidence suggests that climate change is not likely to be a dominant factor in making decisions regarding investment in many green infrastructure schemes. In addition, decisions informed by cost-benefit analysis are only likely to favour such investments when the full range of benefits – particularly the more intangible but real non-market values such as health, amenity, recreational, cultural and environmental regulatory benefits – are included.

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