Generalised Recommendations regarding Passive Control Systems for Improved Air Quality and Climate Change Mitigation
Deliverable 7.2 iSCAPE project

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List of abbreviations

BC:	Black carbon
bVOC:	Biogenic volatile organic compound
CFD:	Computational fluid dynamics
CH_4:	Methane
CO_2:	Carbon dioxide
GHG:	Greenhouse gas
GI:	Green infrastructure
IPCC:	Intergovernmental panel on climate change
iSCAPE:	Improving the smart control of air pollution in Europe
LAD:	Leaf area density
LAI:	Leaf area index
LL:	Living Lab
NO_2:	Nitrogen dioxide
NO_x:	Nitrogen oxides
PCS:	Passive control system
PM:	Particulate matter
PM_1:	PM with aerodynamic diameter <1 µm
$PM_{2.5}$:	PM with aerodynamic diameter <2.5 µm
PM_{10}:	PM with aerodynamic diameter <10 µm
PNC:	Particle number concentration
RCP:	Representative concentration pathway
SEM:	Scanning electron microscope
SLCPs:	Short-lived climate forcing-pollutants
TiO_2:	Titanium oxides
UHI:	Urban heat island
UV:	Ultra-violet
VOC:	Volatile organic compound
WP:	Work package

1. Executive Summary

The purpose of this deliverable is to comprehensively summarise the key findings of work packages (WPs) 1-6 on the infrastructural interventions, including physical passive control systems (PCSs), regarding air quality and climate change. This deliverable synthesises the technical findings of the project in direct terms, and the draft has been shared with the advisory board experts, associated partners and stakeholders in different cities for their formal feedback. Since each city is in close contact with local stakeholders, city authorities and interested parties as a part of Living Lab (LL) activities, the final draft has been shared with them for their feedback on the recommendations via a list of co-created questions by the project team (see the appendix for the feedback). The questions were: (i) What are the steps towards transforming this report into a GI planting guidance document for local citizens, which would comply with building and public resource regulations/codes of practice?; (ii) How can we improve the report and description of our results to provide support to local policy?; (iii) What do you see as next steps on how the project results could be further improved or taken further (e.g. in a continuation project, study etc.)?; (iv) What impact could the report and description of our results have for the municipality, local councils or relevant stakeholders?; and (v) To what extent does the information in this report support your work (in the municipality, local councils or relevant stakeholders) and what other information are you likely to need?. The questions were prepared by different LLs in Guildford (green infrastructural interventions using hedges and trees in open-road and city environments), Bologna (green infrastructural interventions in street canyons, climate change mitigation, interlinkages between air quality and climate change, and photocatalytic coating), Dublin (low-boundary walls or LBWs), Vantaa (air quality-climate change interactions and impacts of green spaces), and Bottrop (urban planning, design, development and behavioural changes). The authors have integrated the feedback into this revised deliverable. Hence, the report's overall recommendations are intended to have a significant impact in improving public health and reducing the costs associated with poor health, particularly of vulnerable people. A short summary of the different research areas and key findings is provided below.

At the local scale, the study on the deployment of green infrastructural interventions using hedges and trees in open-road and city environments by Guildford LL suggested that prior design and implementation of GI is important for improved air quality. The studies showed that planting configurations of relatively dense 'hedges only' and 'hedges combined with trees' as barriers against air pollution, resulted in up to 62% improvement in local air quality under different wind directions and depending upon pollutant type. Further, leaf growth in spring showed a rapid reduction of 52% in particulate matter (PM) concentration immediately downwind of the hedge. Thus, to reduce overall air pollutant concentrations and hence improve local air quality, planting relatively dense 'hedges only' and 'hedges combined with trees' is recommended.

In relation to vegetation barrier design considerations for implementation at the roadside, studies showed that plant species composition can significantly influence its efficacy for air pollution abatement. Thus, general recommendations include: the selection of species that are evergreen or exhibit high foliage longevity; the selection of species with small, rough (e.g. hairy), complex leaves and high crown density; and the avoidance of species that are high emitters of pollen (particularly near vulnerable populations) and biogenic volatile organic compounds (particularly for large-scale planting schemes).

At the city scale, the results of studies under different scenarios indicated that the annual average pollutant deposition varied from 0.2 to 2.77 t yr^{-1} km^{-2} for nitrogen oxides (NO_x), 0.46 to 1.03 t yr^{-1} km^{-2} for PM_{10} (PM less than 10 μm in diameter) and 0.08 to 0.23 t yr^{-1} km^{-2} for $PM_{2.5}$ (PM less than 2.5 μm in diameter) owing to percentage shared with different GI types and traffic emissions. It was also found that the total pollutant concentration reduction could be achieved by a combination of both deposition and the aerodynamic effects of GI. Further, it was also observed that the presence of GI reduced temperatures by 0.85°C during late afternoon (1300h) followed by a 0.6°C temperature reduction during late-night (0100h) and 0.35°C in the late evening (1900h) compared to a GI-free scenario, thus helping to reduce the urban heat island (UHI) effect.

Studies on green infrastructural interventions in street canyon (Bologna LL) revealed that the introduction of trees reduced pollutant concentrations in the proximity of local pollutant hotspots, resulting in more uniform pollutant distribution along the section occupied by street canyons. This effect was enhanced by decreasing the spacing between trees and reducing the cross-sectional area occupied by tree canopies. Further, the studies showed that improvement in thermal comfort generated by the implementation of trees was not limited to the area of the intervention, but that it extended over larger spatial scales and surrounding areas. Thus, trees may be implemented in the future, both in southern and northern Europe, to reduce the impacts of climate change.

The studies on the implementation of photocatalytic coatings indicated average potential reductions of NO_X concentrations in the range 10-20%, reaching up to 40-50% near the painted walls. The reduction depended on the meteorological conditions wind direction affecting the street canyon, in particular on the incidence of clear-sky conditions, and also on the geometry of the buildings, with the largest reductions potentially obtained in shallow or wide street canyon with wind direction perpendicular to the painted walls.

The introduction of LBWs as passive control structures in street canyons was found to have both positive and negative impacts on the air quality inside street canyons. LBWs reduced air pollution at certain sections of the road and footpath, but had the opposite effect in some other sections of street canyons. Studies indicated that the location of LBWs needs to be selected in such a way as to reduce air pollution in sensitive locations of the street, such as schools and office/building entrances. However, it is possible that this may result in air pollutant concentrations increasing at other relatively less sensitive locations. Maximum efficiency in reducing air pollution for pedestrians was noted when LBWs were as continuous as possible. Depending on wind speed and direction, up to a 16-19% improvement in air quality was achieved at certain sections of footpaths in street canyons.

The projected changes in the climates of the cities taking part in the 'Improving the Smart Control of Air Pollution in Europe' (iSCAPE) project, have several common features but also a number of differences. For example, in most cities the highest increases in air temperature are generally simulated to occur in the summer, with increases in diurnal temperature range and incident solar radiation and decreases in precipitation. However, for Vantaa in northern Europe, the most pronounced changes occur in winter. Everywhere under the Representative Concentration Pathway 8.5 (RCP8.5) emission scenario, the projected warming is increasing almost linearly with time during the course of the present century, most rapidly in Vantaa and most gradually in Dublin. The climatological (30-year average) annual mean precipitation is projected to decrease in Bologna and either increase or remain almost unaltered elsewhere. The annual total incident solar radiation is projected to increase in all six cities, most strongly in Bottrop and Hasselt and the least in Vantaa and Dublin.

In relation to climate change, though it is difficult to estimate the direct and indirect impacts of air quality on climate change, the study has indicated that it is likely to lead to ozone (O_3) increases and PM decreases over most of Europe, and especially over southern and central Europe. However, analysing the data collected within the project, some episodes of poor air quality linked to climate change were identified. Studies showed that the implementation of GI and the resulting improvement in air quality was of great benefit in terms of increases in house prices. For example, estimation results showed an added value of 39 €/m^2 for Vantaa and 112 €/m^2 for Bologna for every microgram/m^3 of $PM_{2.5}$ and nitrogen dioxide (NO_2) reduced, respectively. Likewise, an added value of 95 €/m^2 was shown for houses within 100 metres of GI for Vantaa, whilst in Bologna the benefits were 170 €/m^2 and 37 €/m^2 for a 10% increase in the land use share of urban green space and broad-leaved trees, respectively. The health benefits, stemming from reduced morbidity and mortality, of installing LBWs in the most polluted areas of Dublin were estimated to be €4,900 on a regular footpath and €24,000 at cross-sections. The installation cost of a LBW was around €4,500. The non-market economic benefits, stemming from reduced morbidity and mortality, of photocatalytic coating in Bologna resulted in an estimated reduction of NO_2 concentration between 8-17%, corresponding to expected economic benefits of €330 million per year. The installation costs, including materials and labour, were assessed at €36 million per year.

The iSCAPE Living Lab activities proved that air pollution control and climate adaptation should go hand-in-hand for mitigating negative effects on the human-environment system. Therefore, common objectives for preventing air pollution and urban heat islands should be developed and synergies exploited. Furthermore, the Bottrop Living Lab figured out the added value of a comprehensive action plan. This informal strategic policy instrument provides a clear and systematic framework for planners as well as other local decision-makers in the Bottrop Living Lab. It gives an orientation for the complex and demanding task of developing, implementing and reviewing strategies for dealing with the consequences of climate and environmental impacts. Key commonly applicable lessons learned from the application test in the Living Lab environment and identified requirements to efficiently develop and implement an action plan are as follows: (i) good cooperation and networking between different departments of an administration to ensure the exchange of disciplinary perspectives; (ii) support of political decision-makers in the development and implementation of strategies and measures; (iii) involvement of and acceptance by citizens concerning the objectives and measures; (iv) an accompanying sustainable implementation strategy (mainstreaming or dedicated strategy); (v) integration of measures into existing implementation instruments and tools; (vi) monitoring and evaluation; and (vii) personnel resources, financing or subsidies.

2. Introduction

This report comprises all significant findings from WPs 1-6 regarding PCS implementation for air pollution and climate change adaptation and mitigation. It includes an examination of the effectiveness of each PCS undertaken or trialled at each iSCAPE partner city: Bologna (Italy), Bottrop (Germany), Dublin (Ireland), Guildford (England, UK), Hasselt (Belgium), and Vantaa (Finland). While Bologna, Dublin, Guildford and Vantaa were chosen to conduct specific pilot studies to analyse the effects of specific PCSs on air quality. The two cities - Bottrop in Germany and Hasselt in Belgium - were responsible for conducting studies related to the impact of urban infrastructural design and behavioural changes, both in the current scenario and in a climate change perspective. The impacts of behavioural changes and traffic management policies are only briefly mentioned in the following sections, as they are out of scope of this deliverable and are more specific to deliverable 7.3. The viability of the individual intervention(s) tested in each domain is discussed, and the positive or negative effects are analysed and quantified for each pollutant studied. Moreover, any seasonal variation or time restriction of the anticipated effects is highlighted. Figure 1 shows a conceptual diagram linking air pollution sources, greening options, optimized benefits and unintended consequences (Kumar et al., 2019a).

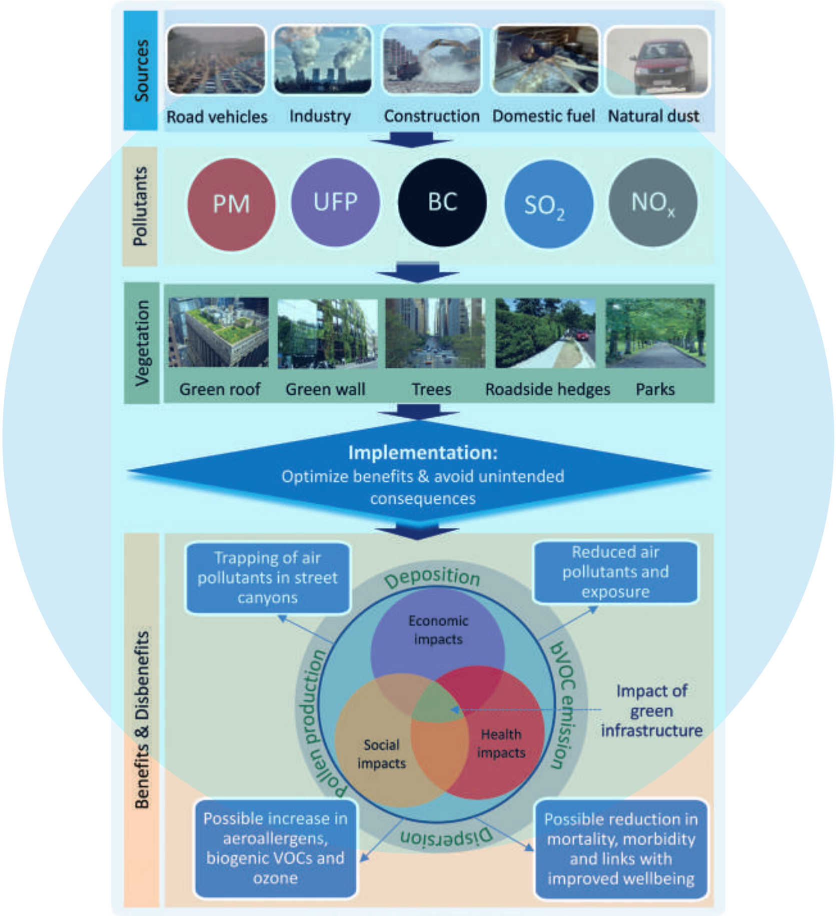


Figure 1. *Conceptual diagram showing the role of vegetation on air pollution mitigation with benefits/disbenefits on economic, health, and social impacts (Kumar et al., 2019a). Reading from the top to the bottom, linking of mitigation of air pollutants through GI installations (e.g. trees and hedges) with improved physical and mental health, socio-economic outcomes and unintended consequences. In the figure, PM: particulate matter ≤ 10 µm (PM_{10}) and ≤ 2.5 µm ($PM_{2.5}$) in diameter; UFP: ultrafine particles (≤ 0.1 µm); BC: black carbon; SO_2: sulphur dioxide.*

The process of delineating European-wide recommendations is naturally limited by the environmental specificities of each city. However, there are many challenges, opportunities, and aspects of urban living that are shared by all iSCAPE partner cities (e.g. that the city has been designed or retrofitted for the car), and it is, therefore, crucial that the iSCAPE cities share knowledge among them (see deliverable 1.1). In addition, most of the recommendations that were implemented in the iSCAPE cities, which are representative of different latitudinal bands in Europe and with various city morphologies, can be extended to other European cities. Furthermore, the knowledge gained by the iSCAPE project needs be disseminated beyond research institutions to policy-makers as well as the general public in order that appropriate interventions are undertaken, both at a societal and at a personal level (i.e. by both a top-down and a bottom-up approach). By working together to determine effective interventions that are applicable under different contexts, the approach taken in formulating this report has generated generic guidelines and policy recommendations regarding the implementation of PCSs for air quality improvement and climate change mitigation that are relevant on a European level.

This report begins by summarising significant findings of the iSCAPE project on effective PCSs for air quality improvement (section 3), before going on to summarise those that were found to be effective for climate change mitigation (section 4) and air quality-climate change interactions (section 5). PCSs are discussed according to influence at two distinct spatial scales (local scale and city scale) and categorised under GI, LBWs, photocatalytic coatings, or urban design considerations. All significant findings are then collated into a series of clear recommendations regarding each PCS category (section 6).

3. Summary of Key Findings on Passive Control Systems: Air Quality Improvement

3.1 General urban planning and design

Cities and urban areas are particularly affected by the negative consequences of air pollution and climate change driven extremes (e.g. floods, heat waves) and face new challenges in adaptation and mitigation. Due to the concentration of assets, sensitive facilities and sensitive groups of people, climatic changes and air pollution can present considerable damage potential. Therefore, activities for adaptation to climate change and the improvement of air quality are essential to support the quality of life and future of our cities and towns. It is the task of the cities to anticipate possible negative effects and adjust their actions proactively with respect to foreseeable challenges. An integrated approach to the development of such necessary policies and measures can be facilitated through appropriate policy guidance and coordination tools and structures. Spatial and urban planning, in particular, offers considerable opportunities for integrated approaches dealing with climate change, strengthening resilience, reducing emissions and promoting sustainable development. In urban climatology research, the interactions and effects between buildings and the local climate (microclimate) are examined in more detail: cities and metropolitan areas cause local climatic effects due to the different physical properties of their surfaces in comparison to the less built-up and greener surroundings, which are generally summarised under the term 'urban climate'. The consequences of the urban climate are an increased thermal level in comparison to the surrounding countryside (UHI), often limited ventilation conditions due in part to dense and tall buildings (e.g. changed wind currents), a greatly modified radiation balance, mostly lower humidity conditions and a deterioration of urban air quality. In addition to the predicted annual mean temperature increase, the number, intensity, and duration of heat waves in Europe will also increase by the end of the century (EEA, 2016a). The associated additional heat load will affect the health of the urban population, which is already negatively affected.

Furthermore, exposure to air pollution, including different particulate and gaseous pollutants, is one of the main health hazards in urban environments worldwide. The combination of pollutant sources and poorly ventilated areas such as narrow street canyons can quickly lead to the accumulation and local concentration of air pollutants above air quality standards (OECD, 2014; WHO, 2016). Increasing air pollution, in particular from NO_2 and PM, is unhealthy for humans and the subject of constant debate.

The urban climate and air pollution bear a considerable influence on human well-being and the quality of life in cities. Many studies on the causes and effects of global climate change have shown that the future design of spatial and urban structures can play an important role in limiting energy consumption and climate-relevant emissions, as well as in mitigating the effects of climate change (EEA, 2016b; Seto et al. 2014). Since the urban climate and emission level (concentration and distribution) are directly related to the design of the environment, changes in the urban structure can modify the local climate and air quality both positively and negatively. The main and general objectives of climate-friendly urban development are, therefore:

1. The improvement of the quality of life and living conditions, especially in densely populated urban areas (reduction in the degree of sealing, provision of urban green spaces, GI) and adaptation of location and

utilisation concepts (e.g. critical infrastructures).

2. The improvement of settlement ventilation and fresh air supply (keeping fresh air corridors clear, protection of cold air development areas, improvement of the urban/bioclimatic climate).
3. The reduction of air pollutants and greenhouse gases or GHGs (climate protection, sustainable mobility, low-emission settlement structures).
4. Precautions against weather and climate related extreme events (heat waves, heavy rain, floods, droughts, strong winds and storms).

Corresponding adaptation measures of urban development are, therefore:

1. The location management of buildings and infrastructures, supply and disposal within settlements and adaptation of buildings (energy optimisation, alignment, shading, albedo).
2. The promotion of compact but nevertheless climate-optimised settlement structures (adapted densification and mixtures of uses) and the protection and development of green, water and open spaces as well as urban water and GIs.
3. The promotion of low-emission settlement and transport structures, including pedestrian and cycle traffic as well as local public transport.
4. The preservation or differentiated regulation of the use of natural areas or areas affected by extreme events.

Measures for air pollution control and climate adaptation should generally lead to avoiding or reducing the impact on the human-environment system. In spatial planning and urban design, the adaptation of an area to climate change as well as a contribution to air pollution control should be formulated as independent development objectives, if analysis and assessment have demonstrated a particular need for action. Other development objectives should be formulated in such a way that they do not conflict with the objectives of climate adaptation and air pollution control; rather, common objectives should be developed and synergies exploited.

The selection, evaluation and priority setting of individual measures should generally be context-dependent and involve political decision-makers, experts, citizens and stakeholders in order to take into account the different perspectives, interests and objectives. This ensures that, on the one hand, existing expertise on the framework conditions and interrelationships of measures are taken into account, and, on the other hand, inquiries, information needs and preferences can be incorporated into the selection of measures. This can increase political and social acceptance and relevance as well as the integration and implementation of adaptation measures.

In the following sub-sections, specific selected measures of case study cities are explained in more detail. The sub-sections cover each PCS's impacts in open-road, street canyon, and city environments.

3.2 PCSs in open-road conditions

This section summarises research findings from deliverables 1.2, 3.2, 5.2 and 6.2. Most of the iSCAPE research findings regarding GI have been published earlier (Abhijith et al., 2017; Abhijith and Kumar, 2019). A general hypothesis exists that GI affects ambient air quality and thereby human health and wellbeing in both positive and negative ways (Kumar et al., 2019a). Air pollution is a complex mixture of nano- to micro-sized particles and gaseous pollutants. Some of the important pollutants in the urban environment are shown in Figure 1. The quantification of changes in the air dispersion or chemical reactions of these air pollutants brought about by GI can allow evaluation of direct or indirect effects of GI on local and regional air quality. Figure 2 shows the removal of atmospheric pollutants by urban vegetation, such as vegetation leaves (dry deposition) and absorption of gaseous pollutants through the stomata. Further details regarding the disadvantages of GI in the built environment can be obtained at Kumar et al. (2019a).

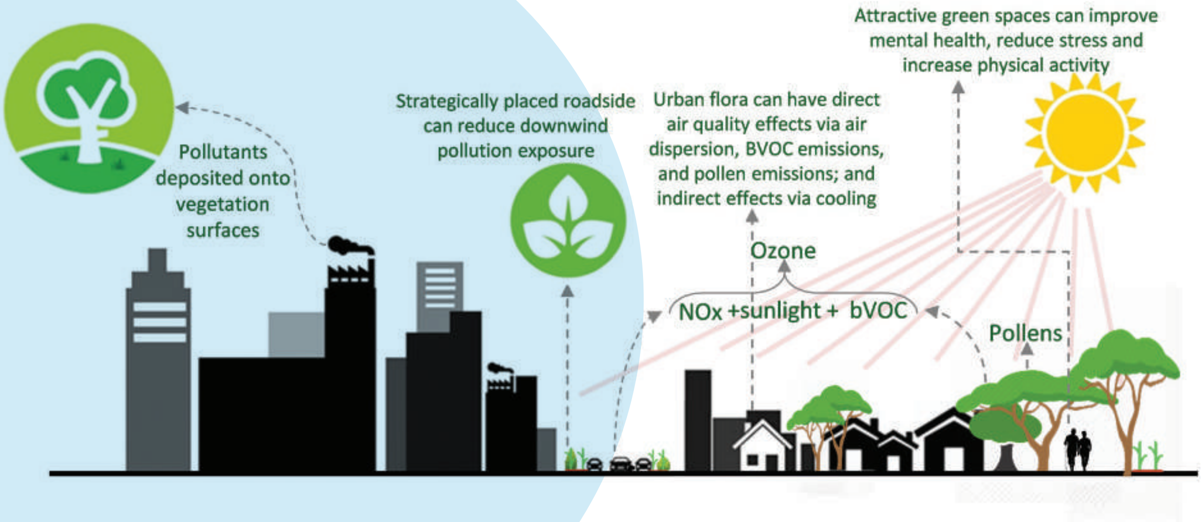


Figure 2. *Schematic diagram showing the air quality benefits and downsides of GI in the built environment (Kumar et al., 2019a).*

Figure 3 shows the overall impacts of GI in both open-road and street canyon environments (Abhijith et al., 2017). In open-road conditions, vegetation barriers with thick, dense and tall vegetation have a generally positive impact on pedestrian-side air quality (Figure 3). Studies observed considerable pollutant removal where vegetation barriers were situated close to the pollutant source and the plume's maximum concentration. In excess of a 50% reduction was observed with a 10 m thick green belt for numerous pollutants. The optimum density for a vegetation barrier was suggested by various studies. Evergreen species were proposed for all year-round vegetation barrier efficacy in open-road conditions. As with research findings from the street canyon studies, the source of pollutants (i.e. local or background) was not differentiated in open-road studies, but these mitigation measures were also considered to have a more significant impact on local emission sources. Relative humidity showed significant impact on pollutant removal by green belts, indicating that climate and regional conditions are important and need to be considered. The impact of vegetation on air quality varied between warmer and cooler climatic regions, which is beyond the scope of the iSCAPE project.

Figure 3. *GI impact on different built environment conditions published in past studies (Abhijith et al., 2017).*

The iSCAPE field campaigns in Guildford assessed three most-common types of GI in open-road configurations, namely hedge-only, tree-only, and tree and hedge combinations. Detailed experimental set-up and methodologies are provided in deliverables 3.2 and 5.2 and outcomes are published in Abhijith and Kumar (2019). The findings are summarised as follows.

The overall data from the field campaign, without segregating by ambient wind directions, suggested that presence of hedge-only (H_{IB}) scenarios resulted in greater improvement in air quality behind GI across all measured pollutants, at both away-road and close-road sites. While combinations of trees-hedge (TH_{IB}-

trees with hedges close-conditions; TH_{CB}-trees with hedges away-conditions) scenarios were found to be the second most effective configuration type in reducing air pollution (Abhijith and Kumar, 2019). The IB and CB subscripts represent 'in-front and behind' and 'clear and behind' of that specific GI, respectively. The tree-only scenarios did not show any positive influences on the measured concentrations. The use of hedges or a combination of hedges and trees, therefore, emerged as favourable options for the reduction of pollutant concentrations behind vegetation.

- *When comparing concentration changes among pollutants, the highest relative differences were observed for BC, followed by PNC (particle number concentration) and* PM_1 *(PM with aerodynamic diameter <1 µm), which was expected due to their modest background concentrations when compared with* PM_{10}*. The lowest relative differences were observed for* $\text{PM}_{2.5}$ *behind the GI.*
- *The assessments based on wind directions revealed a maximum reduction in pollutant concentration during along-road wind conditions, followed by cross-road wind conditions, showing up to a 52, 30, 15, 17 and 31% reduction for BC, PNC,* PM_{10}*,* $\text{PM}_{2.5}$ *and* PM_1*, respectively, as shown in Figure 4.*
- *The analysis of vegetation density indicated higher relative pollutant reductions with an increase in leaf area density (LAD). The difference in PNC (ΔPNC) showed a significant correlation with LAD. GI dimensions such as thickness and height had*

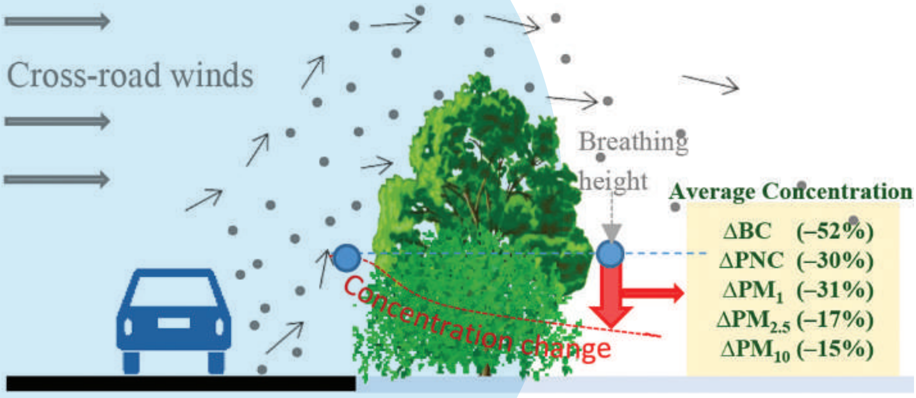


Figure 4. *The above figure was extracted from Abhijith and Kumar (2019), who found pollutant concentration reductions downwind of hedge-tree combination barriers for BC, PNC,* PM_1*,* $\text{PM}_{2.5}$ *and* PM_{10}*.*

an important role in lowering pollutant concentrations behind GI. For example, single tree rows (thinner; T_{CB}) showed a deterioration of air quality compared with multiple tree rows (thicker; T_{IB}), even though both had similar LAD per tree. Similarly, a lower hedge height (H_{CB}) was revealed to be ineffective in reducing pollutant concentrations when compared with a taller hedge (H_{IB}).

- *No change in PM fractional composition was observed behind the GI in the presence of trees. However, both the hedge-only and tree-hedge combination scenarios resulted in lower fractions of sub-micron particles. The SEM single particle analysis revealed a reduction in traffic-related particles (vehicle; −7%) in samples taken from behind the GI compared to those taken in front of, or in a clear area adjacent to, GI. In addition, naturally occurring particles were dominant behind the GI (7%) and agglomerates of particles originating from natural and vehicular sources were lower (−5%) behind the GI. The evidence from the SEM single-particle elemental investigation demonstrated a reduction of harmful traffic-related particles by GI via enhanced dispersion and deposition.*

Ottosen and Kumar (2020) study measured five species (CO, NO_2, PM_1, $PM_{2.5,}$ and PM_{10}), air temperature and relative humidity in front and behind a hedge, using low-cost sensors, over a three months period. To do so, two high-end low-cost air quality monitors were mounted at adult breathing height in front and behind a hedge on the edge of Stoke Park, Guildford, UK (Lon. 51.243999, Lat. –0.571478). Following the approach of Abhijith and Kumar (2019), the leaf area index (LAI) was calculated from the change in photosynthetically active radiation above and below the canopy of the vegetation. The annual vegetation cycles, based on the LAI measurements, were divided into: (i) greenup, "the date of onset of photosynthetic activity" (defined by increasing LAI); (ii) maturity, "the date at which plant leaf green area is maximum" (defined by constant high LAI); (iii) senescence, "the date at which photosynthetic activity and green leaf area begin to rapidly decrease" (defined by decreasing LAI); and (iv) dormancy, "the date at which physiological activity becomes near zero" (defined by constant low LAI). Only dormancy, greenup and part of the maturity phases have been measured in the present study. These long-term measurements were the first step towards an accurate assessment of the city scale air pollution exposure mitigation potential of hedge-like vegetation. The following findings were reported by Ottosen and Kumar (2020):

- *The air pollution concentration in the vicinity of roadside vegetation is dominated by meteorological (e.g. rain), biological (the vegetation cycle) and societal (e.g. public holidays) variables.*

- *The time series of PM measurements show a rapid drop in relative concentrations after leaf emergence, leading to reductions behind the hedge of up to 52% (see Figure 5).*
- *The gaseous pollutants (CO and NO_2) show smaller concentration reductions across the hedge and there is no signal from the vegetation cycle.*
- *Wind direction is shown to be of minor importance.*
- *The exact mechanism of air pollution mitigation by hedges is still very uncertain.*

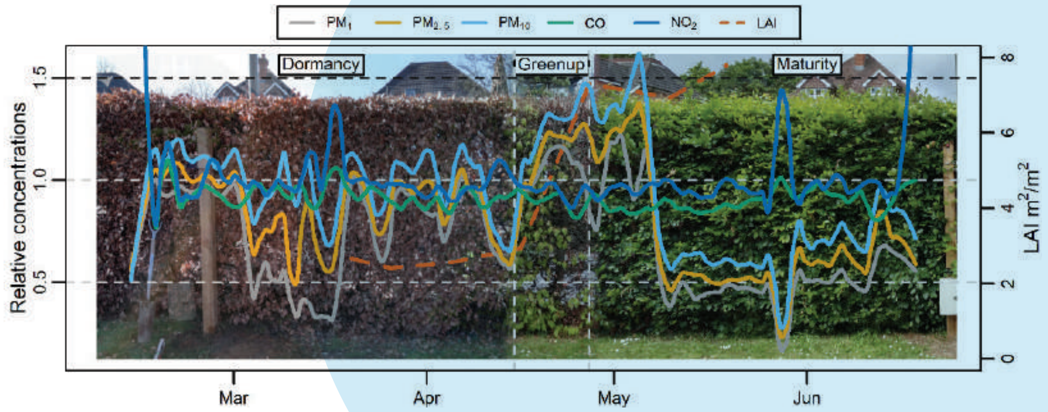


Figure 5. *The magnitude of various controlling variables on the air pollution concentration reductions caused by a hedge through a time-series study (Ottosen and Kumar, 2020). Time duration covers dormancy, greenup, and maturity phases.*

3.3 PCSs in street canyon conditions

3.3.1 Green infrastructure

In street canyon environments, high-level GI (i.e. trees) generally has a negative impact on air quality, whereas low-level, dense vegetation with complete coverage from the ground to the top of the canopy (i.e. hedges) hinders the air flow underneath and hence generally show a positive impact (Abhijith et al., 2017; deliverable 1.2). Even though an oblique wind direction was identified as critical, improvements or deteriorations in air quality in a street canyon depended upon a combination of aspect ratio, vegetation density and wind direction. The results of the iSCAPE project indicate that, although trees in street canyons may increase the pollutant concentrations in local single points, they actually lead to a strong decrease of concentrations in proximity of local hotspots (e.g. traffic intersections and junctions), providing a more uniform and lower pollutant concentrations along the section occupied by street canyons (deliverables 5.3 and 5.4). Decreasing the spacing between trees and reducing the cross-sectional area occupied by tree canopies (through increased pruning and selecting smaller trees with lower foliage densities) can usually reduce street-level personal exposure through increased ventilation. The correct choice of tree species may lead to a 48% reduction of gaseous pollutant concentrations, while the effect on particle pollution can be even higher, with up to a 60% reduction (Abhijith et al., 2017; deliverables 1.2, 5.2, 5.3, and 6.2). Available real-world studies showed that surrounding built-up geometries can alter pollutant concentration profiles in street canyons (Abhijith et al., 2017). It was also noted that the predominant source of pollution in a street canyon environment was vehicular emissions and that findings may, therefore, reflect the impact of GI on local emission sources more than background pollutant contributions. There are a limited number of studies examining hedges in street canyons, with results showing improvements in air quality and a proposed optimum height of hedge in shallow street canyons (Chen et al., 2015; Gromke et al., 2016; Li et al., 2016b; Vos et al., 2013; Wania et al., 2012). Detailed studies are required to provide favourable hedge dimensions and densities in different aspect ratios and meteorological conditions.

The combination of vegetation and solid passive air pollution control measures has the potential to maximise pollutant concentration reductions and improve personal exposure conditions, more than that which may be achieved by any individual intervention in both street canyon and open-road conditions.

3.3.2 Green roof/wall

Only a small number of studies investigated air quality improvements related to green roofs and green walls. Reported air pollutant reductions by green walls ranged up to 95% (as compared to green wall free scenarios) and, in the case of green roofs, from 2% to 52% (Abhijith et al., 2017; deliverable 1.2). However, the ability of green walls and/or green roofs to remove pollutants was less than that of trees and vegetation barriers. Pollution reduction by green roofs was also inferior to that of green walls. These interventions require less spatial requirements than trees and green belts and can be part of building surfaces and structures such as bridges, fly-overs, retaining walls, and noise barriers. Further investigations are required to produce generic recommendations. In any case, in the examinations performed in Finland, the presence/vicinity of GI in general has effect on the housing prices and to the conformity of the citizens. The closer the GI, the higher is on average the value in euros and satisfaction (Votsis, 2017).

3.3.3 Low boundary walls

Introduction of LBWs as passive control structure at street canyon can have both positive as well as negative impact on the air quality. The reduction and increase in air pollution at the footpaths due to presence of LBWs depends on meteorological factors such as wind speed and wind direction and the canyon geometry. Simulation studies performed using computational fluid dynamics (CFD) models indicated that in perpendicular wind conditions a 16-19% improvement in air pollution can be achieved at certain sections of the footpaths, while in other sections the air quality can deteriorate by an amount of 21-25% (Gallagher, 2013a; Gallagher et al., 2013b). In situations where the wind flow is along the predominant direction, the maximum reduction in air pollution was found to be 7% while a 5% increase in pollution were noted. Based on the analysis, it can be concluded that by installing LBWs between the footpath and the street, air quality can be improved at certain important locations along the street canyon, such as schools and hospitals.

3.3.4 Photocatalytic coating

Prior to the iSCAPE project, the effect of photocatalytic coatings was analysed in real-world street canyons in a few experiments, with mixed results. One experimental monitoring campaign was developed and carried out at Lazzaretto campus of the University of Bologna in August 2018, and aimed to analyse and characterise the effect of photocatalytic coatings in real-world conditions. Results indicate a preliminary reduction in NO_X concentrations in the range 10-20% (deliverable 3.8). Additionally, data obtained during the campaign was utilized to validate CFD simulations conducted at the neighbourhood scale in the investigated street canyon (deliverable 3.6). Once verified against observations, the aim of CFD simulations is to extend the results on the efficacy of the coatings to other European cities characterized by different solar radiation and temperature conditions.

The simulations showed that the potential of photocatalytic coatings in reducing NO_X concentrations depends on the meteorological conditions affecting the street canyon, and particularly on the incidence of clear-sky conditions, but also on the geometry of the buildings. The highest reductions are observed when the walls and the street are exposed to maximum ultra-violet (UV) radiation, i.e. at about noon. The reduction is also dependent on the distance from the painted walls, with the greatest reductions occurring in the first 25-50cm from the painted walls. Average NO_x reductions are in the range of 10-20%, but also up to 40-50% near the painted walls. The presence of shadows on parts of the coated walls may further enhance the potential effectiveness of photocatalytic coatings. In winter, during sunny days, the reduction at noon can be higher than that observed in a summer afternoon, when some of the walls are in the shadows.

3.4 PCSs in city environments

3.4.1 Urban air quality

At the city scale, GI can bring health benefits by decreasing annual air pollutant concentration levels through the combined effects of GI-induced aerodynamic dispersion and surface deposition. The research findings related to air pollution mitigation via different GI in a city environment are documented in deliverables 5.3 and 6.3 and relevant journal articles (Tiwari et al., 2019a, 2019b). Studies reported that pollutant removal via deposition over GI surfaces depends on the pollutant concentration levels and deposition velocities of pollutants. Many research studies suggested that coniferous trees with high LAD are more effective than grassland and deciduous trees. Figure 6 shows the impact of various GI types at different spatial scales for air pollution mitigation and exposure control.

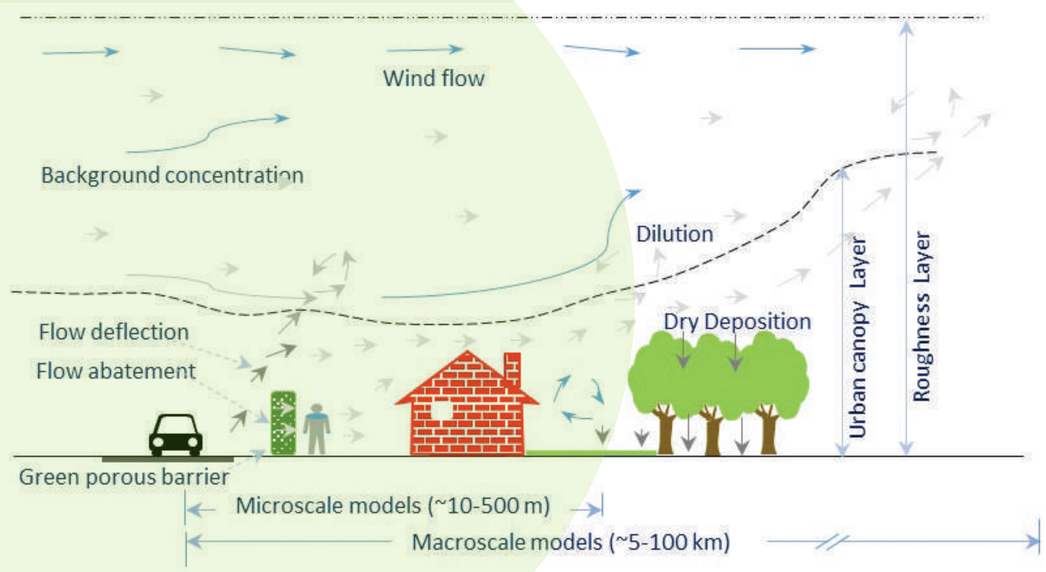


Figure 6. *GI influenced processes (aerodynamic effect and dry deposition) at different length scales (Tiwari et al., 2019a).*

Tiwari et al. (2019b) simulated GI-influenced annual air pollutant concentration maps using a computational dispersion model (ADMS-Urban, developed by Cambridge Environmental Research Consultants, UK), comparing different GI scenarios for the present (year 2015) and the future (year 2039) in Guildford, UK, as a case study. Detailed experimental set-up and methodologies are provided in deliverables 5.3 and 6.3, and outcomes are available in Tiwari et al. (2019b). The summarised findings are as follows:

- *GI cover (~75% of total area) in the urban area could result in a reduction in pollutant concentration levels from a few percentages to about 35%, depending upon plant species and pollutant types.*

- *The annual average pollutant deposition varies according to the percentage share of different plant species and pollutant concentrations over the surface.*
- *Air pollutant depositions are greater for trees when compared with grass areas, owing to enhanced air turbulence promoted by trees, which in turn increases the probability of pollutant interactions with trees rather than with grass.*
- *Evergreen trees attract more pollutant deposition than deciduous trees, due to the availability of leaves throughout the year.*
- *Evergreen trees with high LAD reduce downwind air pollutant concentrations via enhanced dilution owing to atmospheric turbulence.*

Similar results were also obtained with the same dispersion model but adopting a different approach to simulate GI in Bologna, Italy (deliverables 6.3 and 6.5). Conversely, when applying similar interventions in Vantaa, Finland, where pollutant concentrations are very low compared with the other cities, the results indicated a negligible impact of GI on pollutant concentrations.

Summarizing, an increase in GI cover in the urban area can produce a great reduction in pollutant concentration levels, which depends on the chosen plant species and the pollutant type/levels. In general, the correct choice of tree species depends also on the allergenic potential (Kumar et al., 2019b), which was not investigated in the iSCAPE project.

3.4.2 Urban heat island

Urbanisation, with replaced open land or water areas and densely packed urban (grey) infrastructures, contributes to high thermal absorption, which in turn exhibits warmer temperatures than its surrounding suburban and rural areas (Santamouris et al., 1999). This phenomenon of cities, recording higher temperatures than their non-urbanized surroundings, is known as the UHI effect.

Numerous research studies have discussed the importance of UHI mitigation. One approach that has gained attraction in recent years is to implement GI to mitigate UHI formation. For instance, the implementation of GI showed a reduction of up to 2°C by green roofs (Razzaghmanesh et al., 2016; Susca et al., 2011) and 3.4°C by green walls (Alexandri and Jones, 2008), especially in humid and drier climates, where the surface heat is emitted at a higher rate in green walls compared to conventional concrete walls and 1-2°C for GIs (Perini and Magliocco, 2014).

The iSCAPE research outcomes related to UHI mitigation by GI at urban scale have been documented in deliverables 6.3 and 6.5. Results indicate that the introduction of GI mitigates UHI with improvements in thermal comfort on the order of 1-2°C in northern, central and southern Europe. In addition, it has been demonstrated that the impact of the introduction of GI is not only limited to the area of the intervention but extends over surrounding areas.

Further, GI plays a vital role in the evapotranspiration process, which in turn reduces heat emissions from surrounding buildings and absorbed solar radiation emissions from various forms of urban fabrics (Figure 7).

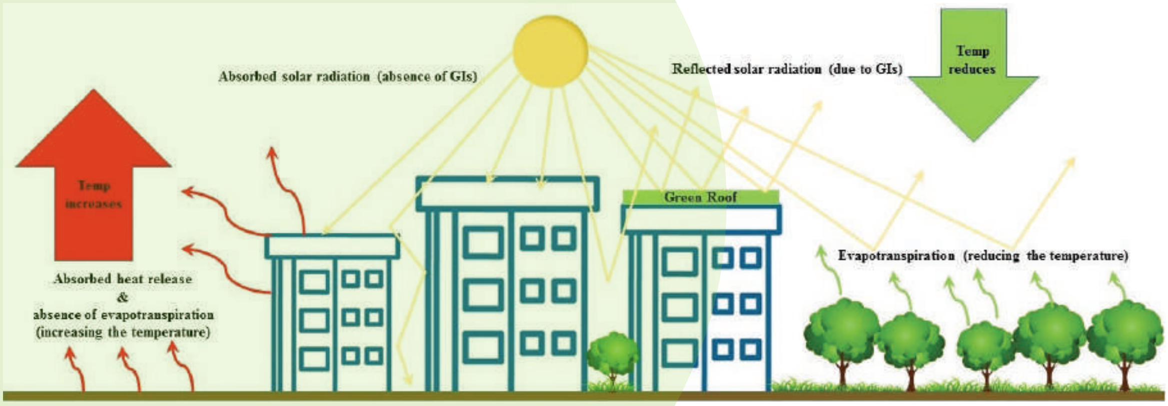


Figure 7. *Influence of GIs in reducing the temperature in an urban area (Kalaiarasan et al., in preparation).*

Kalaiarasan et al. (in preparation) simulated the impact of GI at a macro-scale for three different landforms (urban area, urban residential area, and suburban residential area) using a dispersion model (ADMS-Urban, developed by Cambridge Environmental Research Consultants, UK) for the existing scenario (year 2015) in Guildford, as seen in Figure 8. Further, to estimate the best-suited GI for UHI mitigation, four different scenarios were formulated using the existing scenario as the baseline scenario. Detailed information regarding the methodology and formulation of scenarios has been provided in deliverable 6.3, and the outcomes of the research will be published in Kalaiarasan et al. (in preparation). The findings are summarised as follows:

- *GI plays an important role in reducing UHI effects, even in the presence of anthropogenic sources.*

- *Urban fabric coupled with anthropogenic emissions in any urban area were found to sway in rising the temperature and leading to UHI formation.*
- *Evapotranspiration associated with GI (green roofs, hedges, trees in large street canyons, etc.) reduces temperatures significantly.*
- *Green roofs alter the albedo from concrete roofs considerably and increase the emissivity of solar radiation, causing a decline in urban fabric heat absorption, which leads to reduced nocturnal heat release from buildings.*
- *The temperature perturbation reduction is found to be higher when the GI is assumed to be trees. The higher surface roughness of trees and increased wind speed due to trees aids in reducing the temperature rise and causing a positive effect in mitigating UHI formation in urban environments.*

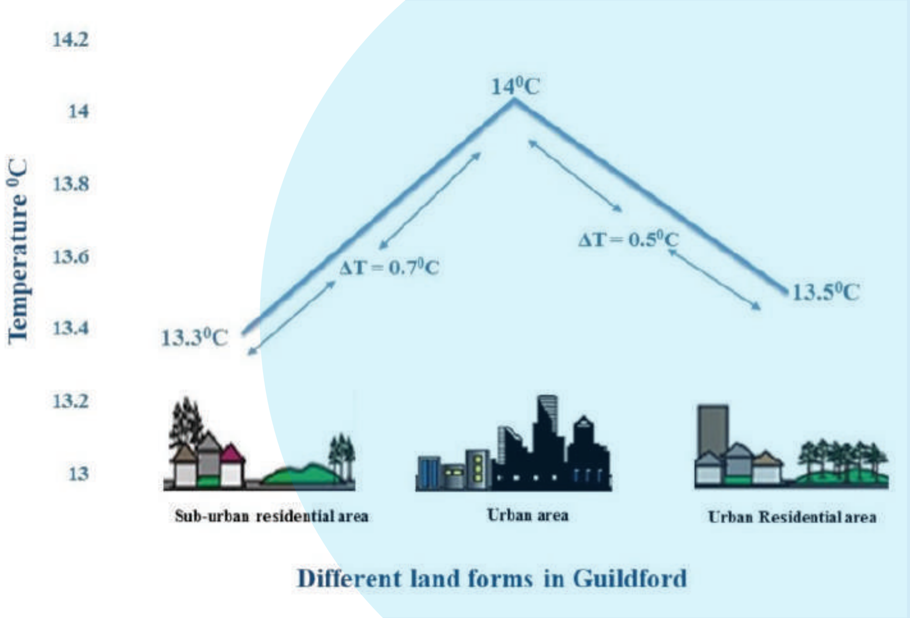


Figure 8. *Modelled temperatures for different land forms (Kalaiarasan et al., in preparation).*

4. Climate Change

4.1 Impact of climate change over Europe

Climate change is already visible globally as well in Europe. The most notable changes are visible in the increase of average temperatures (Figures 9 and 10) but also in the temperature extremes. These changes can be clearly attributed to anthropogenic origin, as described e.g. by the Intergovernmental Panel on Climate Change or IPCC (IPCC, 2013). The increase in temperatures affect the water cycle as well: warmer air (i.e., atmosphere) can hold more moisture and the higher temperatures lead to higher evaporation in general, together leading to increased heavy precipitation in western Europe and droughts in southern Europe (Forzieri et al., 2016).

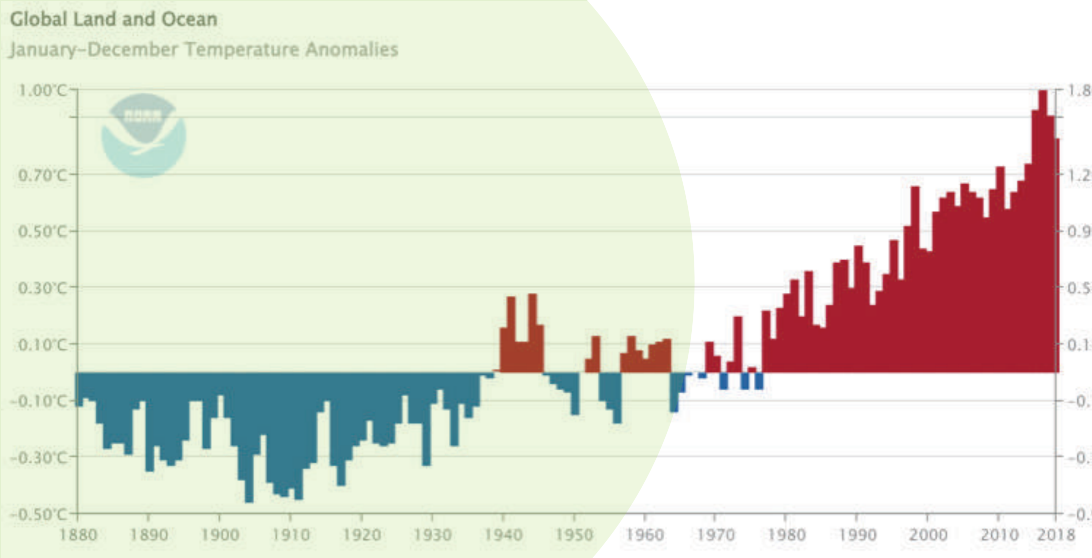


Figure 9 . *Annual global (land and ocean) temperature anomalies with respect to the 20th century average. From: NOAA National Centre for Environmental Information, Climate at a Glance: Global Time Series, published August 2019, retrieved on September 7, 2019 from https://www.ncdc.noaa.gov/cag/.*

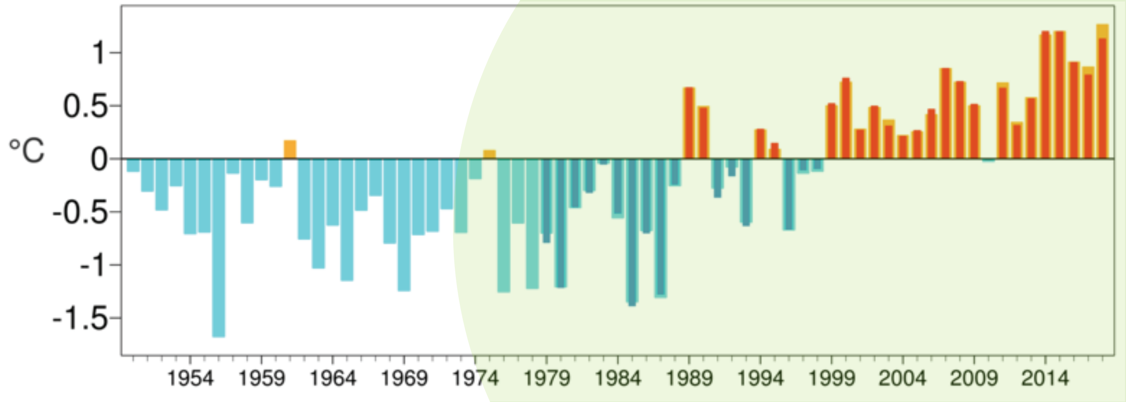


Figure 10 . *European surface air temperature anomaly for annual averages from 1950 to 2018, relative to the annual average for the period 1981-2010. Data source: ERA5 (i.e., reanalysis; dark blue and red, starting 1979) and E-OBS (i.e., surface observations; light blue and yellow). Credit: Copernicus Climate Change Service (C3S)/ECMWF/KNMI.*

How much the climate change globally and regionally, and the type of impact this has, depends heavily on GHG emissions (Figure 11). A pathway of high emissions leads to a steady, continuous increase in global temperatures (RCP8.5 in Figure 11), while substantial reductions in emissions will lead to stabilisation of global temperature.

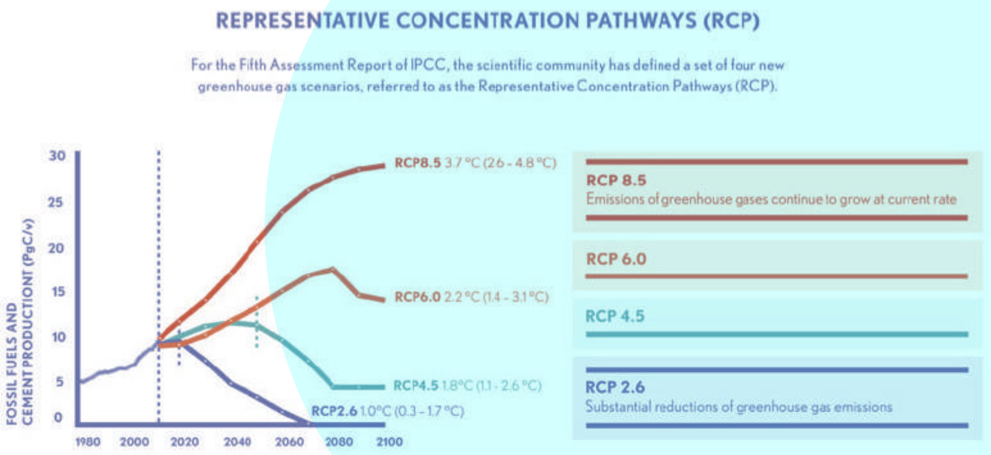


Figure 11. *RCP-scenarios used by IPCC and related expected changes in the global mean temperature (here relative to the period 1986-2005). From: Climateguide.fi.*

Europe extends latitudinally from the sub-tropical Mediterranean regions to the cold Arctic, and longitudinally from the moist maritime Atlantic climate to the dominantly continental climate in the East. Accordingly, climatic changes vary highly with respect to the region (Figure 12).

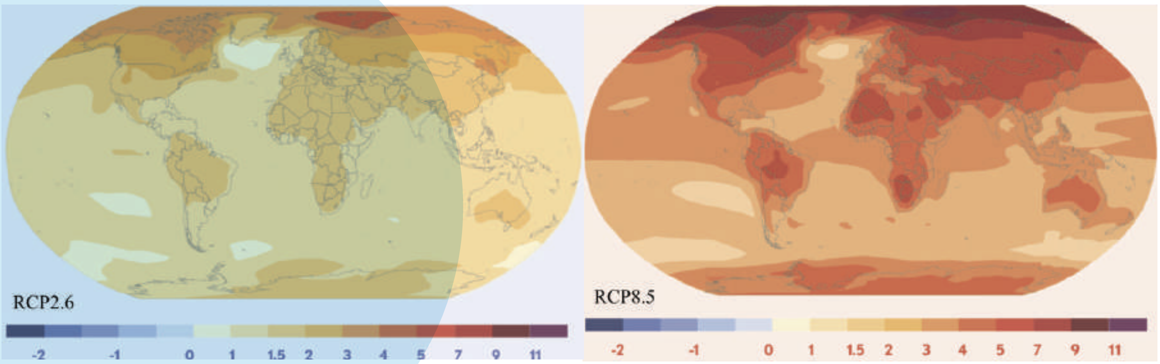
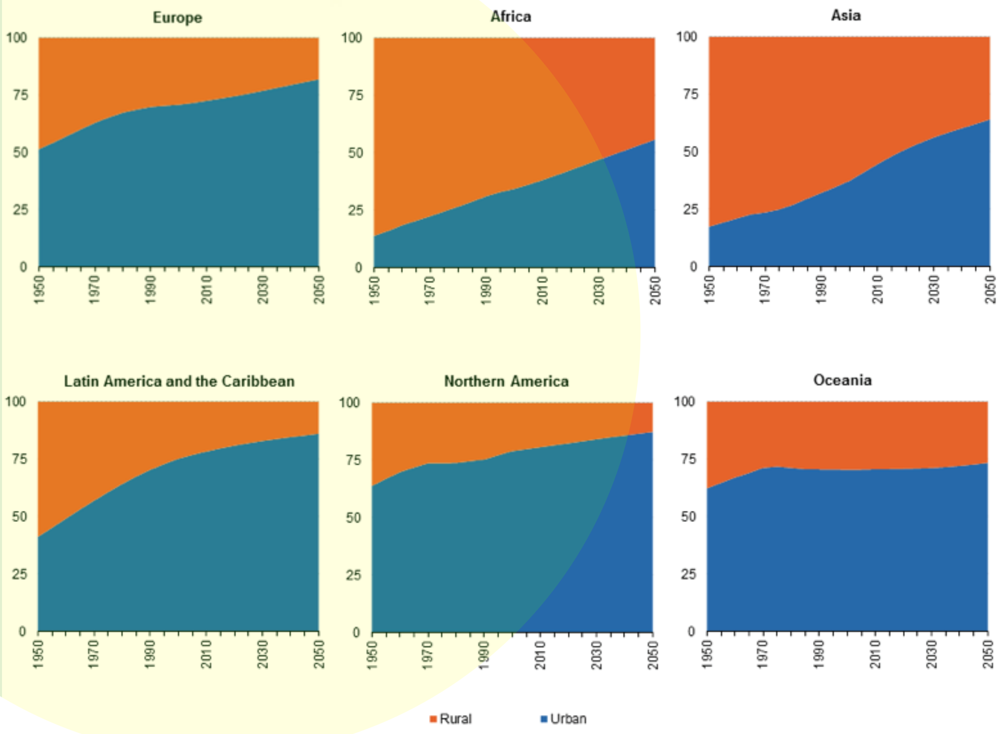


Figure 12. *Predicted change in average temperature (°C) with respect to period 1986-2005 according to RCP2.6 (upper) and RCP8.5 (lower) emission scenarios. From: Climateguide.fi.*

Cities and urban areas have become increasingly populated during recent decades and this trend is expected to continue throughout the 21st century (Figure 13). In Europe, the proportion of the population living in urban areas is expected to reach about 80% by 2050. This means that the impact of climate change on urban areas will affect more and more people in the coming years.



(*) United Nations data are based on national definitions; as such there may be a discrepancy with respect to the Eurostat data used elsewhere in this publication.

Figure 13. *Share of urban and rural populations, 1950–2050*[1] *(% of the total population). Source: World urbanisation prospects - United Nations, Department of Economic and Social Affairs, Population Division (2014).*

In the following, we describe expected climate change impacts in different parts of Europe, following the geographical positions of the iSCAPE cities in southern (Bologna), Central (Bottrop, Hasselt, Dublin, Guildford) and northern (Vantaa) Europe.

The projected climatic changes in the iSCAPE cities positioned in different parts of Europe have several common features but also clear differences (Figures 14 and 15). Everywhere under a high-emission scenario of RCP8.5, the projected warming is expected to increase throughout the 21st century, most rapidly in Vantaa (northern Europe) and slowest in Dublin (maritime climate in central Europe). Apart from Vantaa, the projected annual mean increases in daily maximum temperature are larger than those in daily minimum temperatures. The annual mean precipitation is projected to decrease in Bologna and either increase or remain almost unaltered elsewhere else. Another common feature for all six iSCAPE cities is that the projected changes do not distribute evenly throughout the year.

The following changes in climate are expected to take place in the test case EU cities by 2050:

- *In Bologna, there is a general trend towards higher temperatures and more solar radiation, particularly so in summer, increases in diurnal temperature range and day-to-day temperature variability during the warmer half of the year, and reductions in summer precipitation. Minor decreases in mean wind speed might occur in autumn and some turning of wind directions in summer and winter.*
- *The projected changes in temperature and precipitation in Bottrop resemble those for Bologna but are in general weaker. In contrast, solar radiation in summer and autumn is expected to increase even more strongly than in Bologna. In winter, there might be slight increases in mean wind speeds in the portion of southwesterly winds in winter and decreases in south-westerly winds in summer.*
- *Among the six iSCAPE cities, the projected long-term trend of warming is weakest in Dublin, both on an annual and on a monthly basis. Also, the relative increase in annual insolation is lower in Dublin than in most of the other iSCAPE cities. The same is true for increases in the diurnal temperature range in summer. Instead, the projected percentage decreases in summer precipitation amounts and increases in day-to-day variability in daily mean temperatures in summer are of average magnitude, whereas decreases in the mean wind in summer are slightly larger (or less minor), although with high uncertainty, than in most of the other iSCAPE cities.*
- *The climate projections for Guilford resemble those for Dublin in several aspects, but the changes are generally larger. The percentage increase in summertime diurnal temperature range is about twice as large as in Dublin, and annual mean solar radiation flux is projected to increase approximately at the same rate as in Bologna, although not as rapidly as in Bottrop and Hasselt.*
- *The climate projections for Hasselt are very similar to those for the nearest iSCAPE city, Bottrop. There is a general trend towards higher temperatures, particularly so in summer, slightly wetter winters and drier summers, more solar radiation and little changes in mean wind speed. The multi-model mean projections show slight increases (decreases) in the portion of southwesterly winds in winter (summer), particularly for Hasselt.*
- *The projected future changes in the climate of Vantaa deviate from those for the other iSCAPE cities. There is a general trend towards higher temperatures, but unlike in other cities, the trend is stronger in winter than in summer. Also, the*

projected changes in precipitation and solar radiation are more pronounced in winter than in summer rather than vice versa. A similarity with the rest of the iSCAPE cities is that the multi-model mean changes in the mean wind speed are small compared to the uncertainty ranges.

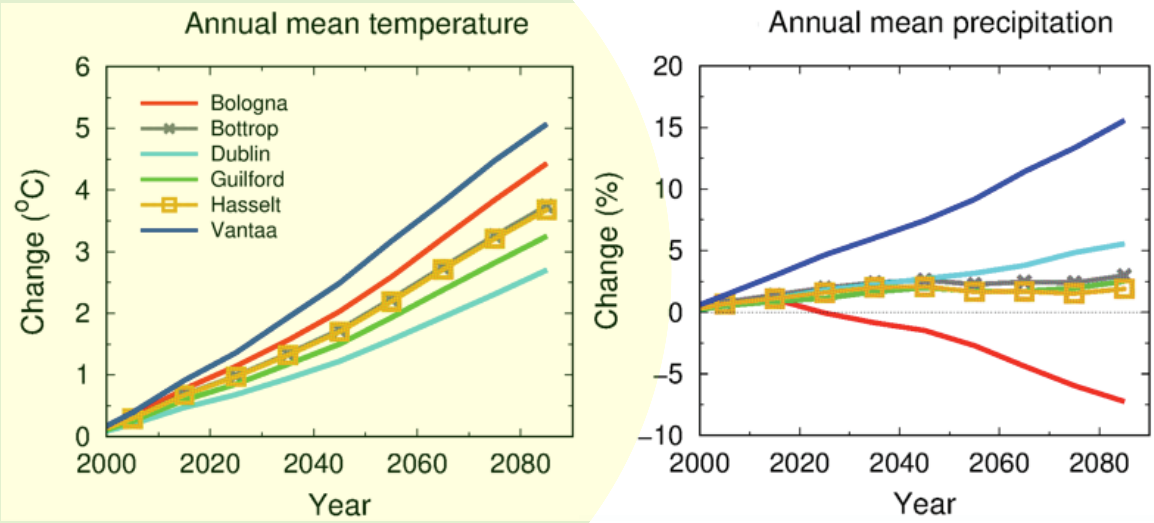


***Figure 14.** Predicted change in annual mean temperature (left) and precipitation in iSCAPE cities according to RCP8.5 scenario (Source: deliverable 6.4).*

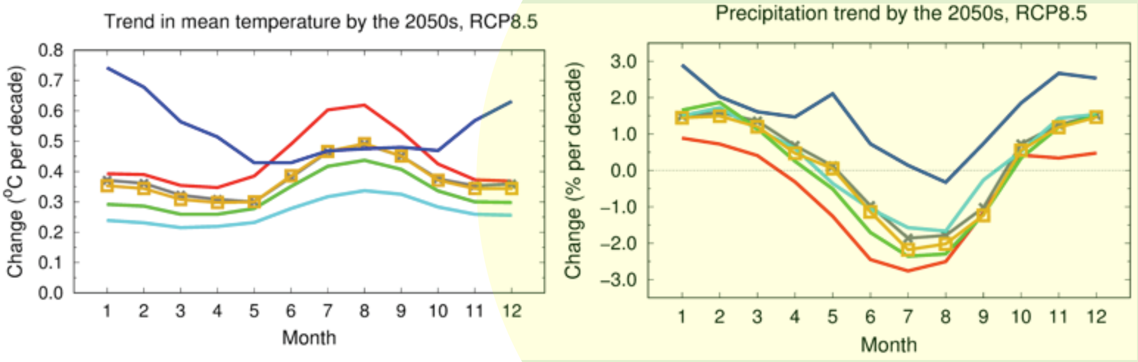


***Figure 15.** Monthly trends in mean temperature (left) and precipitation in iSCAPE cities by the 2050s according to RCP8.5 scenario. The line definitions of the lines are the same as in Figure 14 (Source: deliverable 6.4).*

4.2 Key strategies to mitigate climate change

4.2.1 Physical interventions

The latest report from the United Nations IPCC (IPCC, 2018), grouping scientists from 195 countries, reached consensus on the human contribution to global warming, producing a likely range of 0.8 to 1.2°C global temperature increases with respect to pre-industrial levels, and reaching 1.5°C between 2030 and 2052 time frame if temperature increases at the same rate.

Under this scenario, extreme weather and climate related events such as heat waves are predicted to become more intense, longer-lasting, and/or more frequent (IPCC, 2018).

Besides the urgent need to reduce the emissions of GHGs switching towards renewable and sustainable energy technologies, the IPCC report also suggests proceeding with carbon dioxide (CO_2) removal in order to reduce the concentrations of gases that are already in the atmosphere. In this framework, "reforestation and ecosystem restoration" and similar nature-based solutions are the only methods recognized to be effective (see Figure 16).

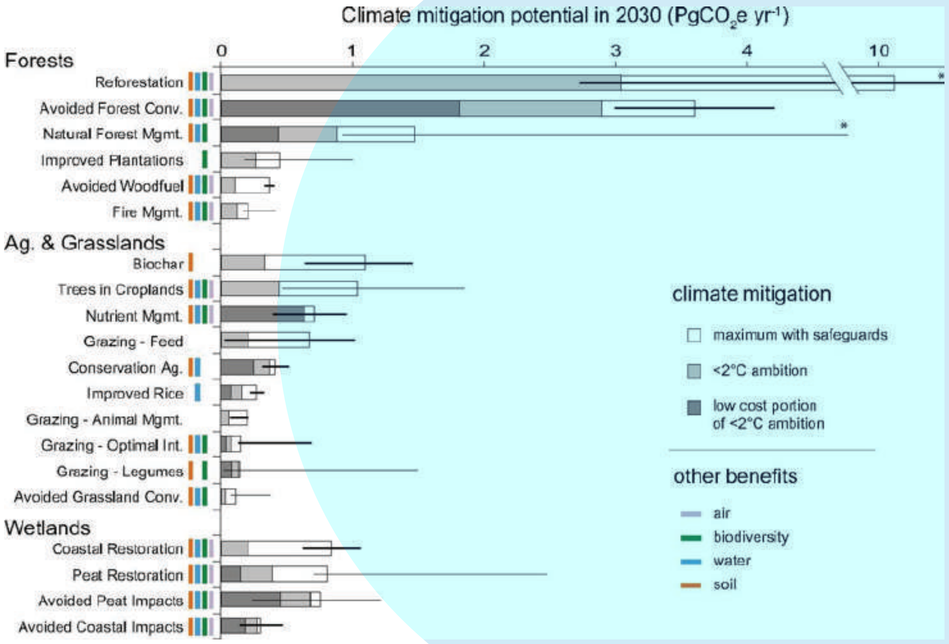


Figure 16. *Climate mitigation potential of 20 natural pathways for the reference year 2030 (Griscom et al., 2017).*

In particular, GI plays a pivotal role in addressing and mitigating climate change:

1. *Trees absorb carbon and other gases from the atmosphere;*
2. *Trees provide shade, which in urban areas might be helpful in reducing energy consumption, reducing emissions and saving on cooling costs.*

Urban street trees have been recognized as providing many benefits for our cities, including the reduction of building energy use (Bowler et al., 2019) and high urban temperatures, the mitigation of UHI effects (Loughner et al., 2012) and climate change (Matthews et al., 2015), leading to an overall improvement in thermal comfort (Shashua-Bar et al., 2010).

The impact of GI on UHI effects and thermal comfort was analysed with two intensive thermographic campaigns in Bologna (deliverable 5.2), a city well representative of southern Europe. The comparison of air and building temperatures recorded in one vegetated and one non-vegetated canyon indicates that vegetation improves urban thermal comfort and reduces the UHI effect (i.e. the fact that the metropolitan area is warmer than the rural area surrounding it) of about 2°C in the summer season (i.e., when urban thermal comfort is less) (Figure 17).

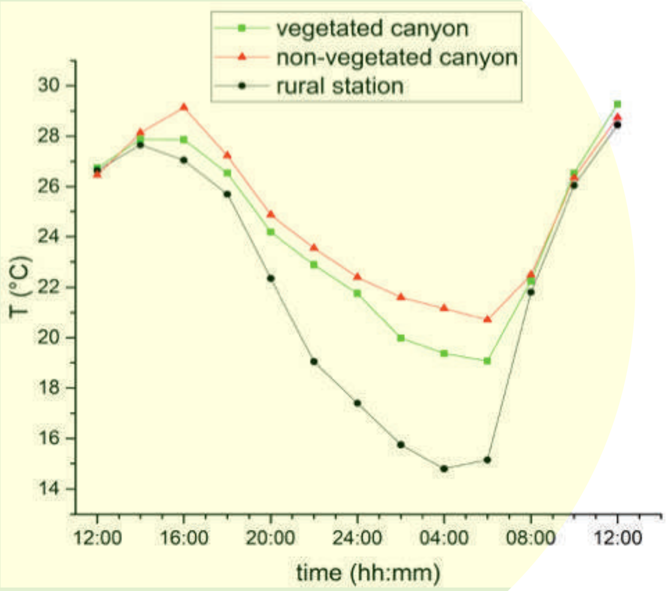


Figure 17. *Temperature diurnal evolution within the day of the summer intensive thermographic campaign in Bologna (22-23/08/2017), measured by the thermo-hygrometers in one vegetated and one non-vegetated canyon, and at one rural meteorological station from ARPAE Regional Environmental Protection Agency (source: deliverable 5.2).*

Simulations conducted in a neighbourhood of the vegetated canyon, verified against observations, indicate that the improvement in thermal comfort is not limited to the area of the intervention but extends over larger spatial scales and surrounding areas (deliverable 6.3 and 6.5). The results of simulations conducted in a climate change scenario (RCP8.5 "business-as-usual" previously described) indicate that the temperature reduction and improvement in thermal comfort obtained with trees may be maintained in the future, with a 2°C temperature reduction obtained when comparing a scenario with trees with one without trees (Figure 18).

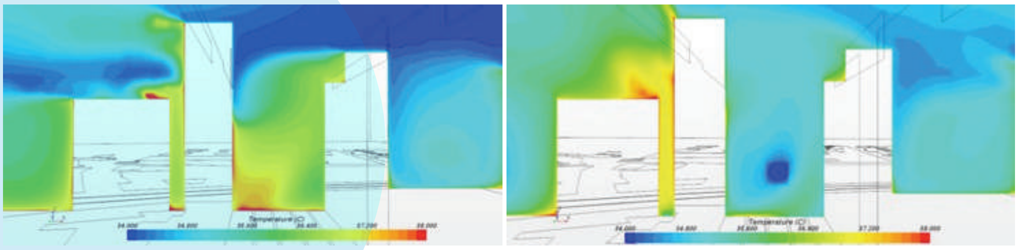


Figure 18. *Comparison of air temperature obtained for a future August day in the same street canyon without trees (left) and with trees (right) (source: deliverable 6.5).*

Similar results are also obtained for the city of Vantaa in northern Europe, where the impact of replacing a dense urban landscape by a sub-urban landscape enables reductions of temperature as high as -0.4 - 0.8°C in the future climate scenario (RCP8.5 scenario previously described), with higher reductions in the summer period (Figure 19).

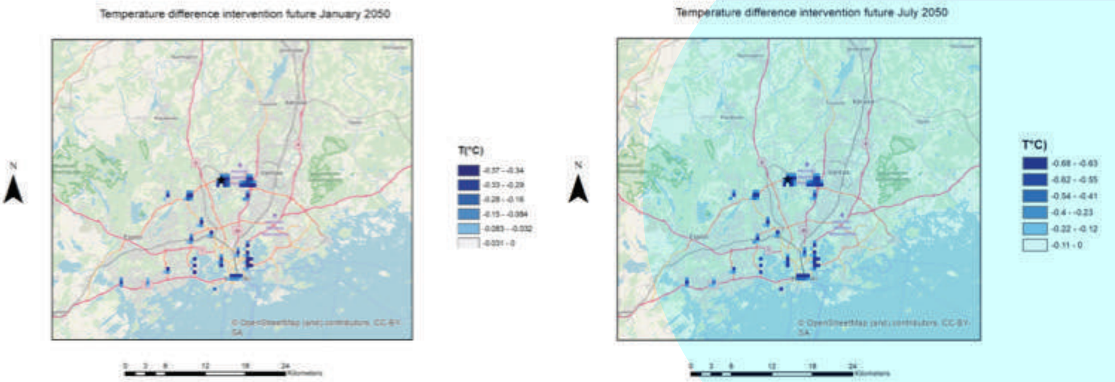


Figure 19. *Maps of the temperature difference between the intervention scenario with trees and the scenario considering only climate change in future January (left) and July (right) in northern Europe (Vantaa) (source: deliverable 6.5).*

4.2.2 Behavioural changes

A recent report from Rare's Centre for Behaviour & the Environment (Williamson et al., 2018) quantifies the impact that behaviour change can have on curbing GHG emissions. The report analysed the impact of 80 climate solutions outlined in the Drawdown project (https://www.drawdown.org/), a comprehensive plan to mitigate global warming, and found that individual behaviour can play a significant role in 30 of them. The detailed analysis of these 30 solutions, which fall across four different sectors (food, transport, energy and materials, and agriculture and land management), found that the adoption of these solutions at a full level can cut down one-third of the projected global emissions between 2020 and 2050.

The impact of behavioural changes was also investigated in the iSCAPE project, where the focus was mostly on the transport sector. In particular, the outcomes of different traffic management policies, analysed in three cities that are representative of three different latitudinal bands but share the same major pollutant emission sources (i.e. traffic and residential heating), and where climate change is projected to impact differently, are reported in deliverable 4.5. Behavioural changes were investigated through the implementation of traffic management policies, such as closures of parts of the city centres to road vehicles, prohibition of non-electric vehicles in the city centres, and increases in the bus frequency to support the individual choice of public transportation instead of private vehicles (more details are available in deliverables 4.4 and 7.3). These behavioural changes are in general also considered in the Rare's Centre report, which indicates the greatest reductions in GHG emissions achieved through the shift to electric vehicles (up to 50% reduction).

Accordingly, our results indicate that closure of the urban city centres to non-electric vehicles is the best option to adopt both in the current scenario and in a climate change perspective. Instead, the use of public transportation rather than individual vehicles for commuting in cities might curb GHG emissions (up to 26% upon Rare's report), even though the increase in the emissions of particles through non-exhaust emissions occurring in all scenarios of higher frequency of the buses demonstrated that this policy might have adverse counter effects on air quality.

5. Air Quality-Climate Change Interactions

Air pollution and climate change are closely related through multiple linkages. Many sources of air pollutants, among which the extraction and burning of fossil fuels is predominant, also emit CO_2, other GHGs and particles that affect climate (Fiore et al., 2015). In turn, climate change influences air pollution by intensifying meteorological conditions and pollutant dispersion and accumulation. The following schematic diagram (Figure 20) presents the various links and interferences between air quality and climate change.

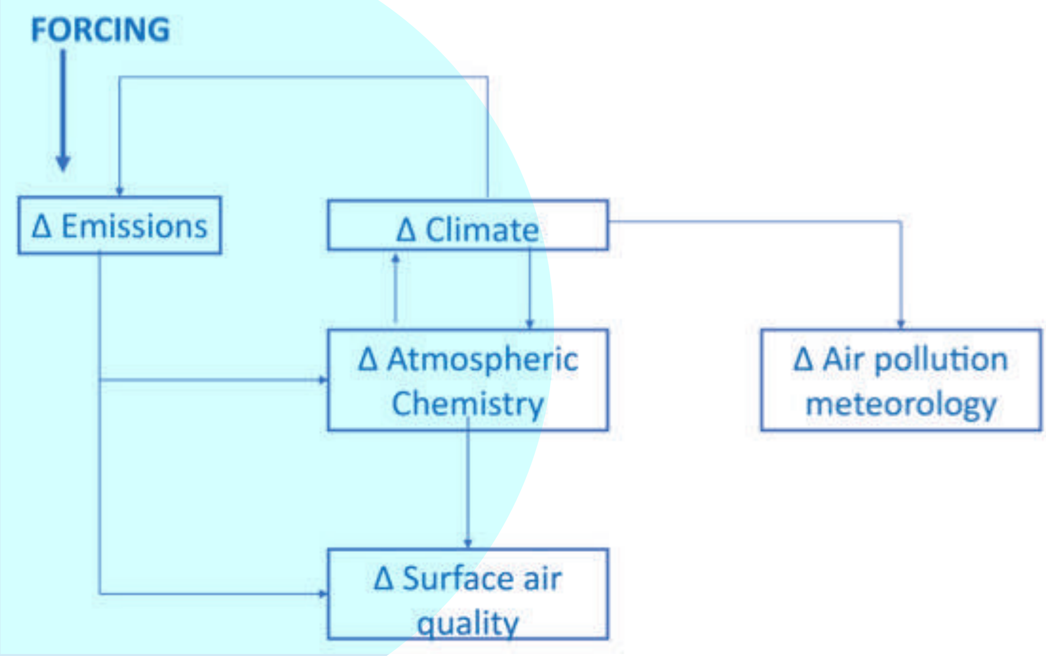


Figure 20. *Interactions between air quality and climate in the broader context of chemistry-climate interactions (from Jacob and Winner, 2009).*

Figure 21 schematically illustrates the main links and interactions between air quality and climate change. In the next section, these two interrelated global issues are summarized, and action plans to mitigate air quality-climate interactions are presented.

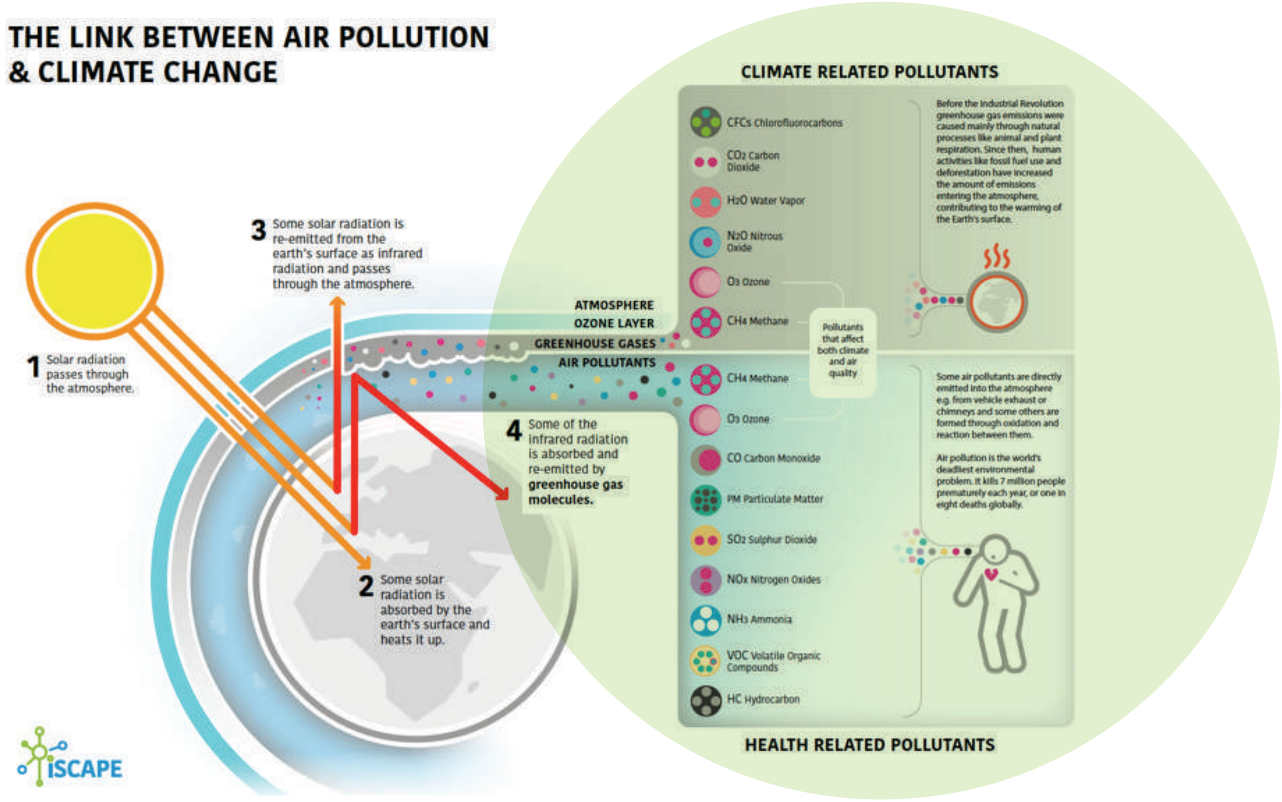


Figure 21. *Interlinkages between air quality and climate change. From iSCAPE report deliverable 2.4 (https://www.iscapeproject.eu/scientific-reports/#stak).*

5.1 Climate change effects on air quality

Air quality depends strongly on weather and therefore on climate change and related modifications in atmospheric circulation and precipitation patterns. It is well recognized that, irrespective of high emissions, air quality issues are more likely to emerge in stagnant weather conditions. Meteorological variables such as temperature, humidity, wind speed and direction, and mixing height (i.e. the vertical height of mixing in the atmosphere) drive air quality patterns over multiple scales in time and space (Kinney, 2008).

Modifications in the frequency, severity, and duration of heat waves, air stagnation, and other meteorological events related to pollutant accumulation and dispersion greatly influence air quality (e.g. Ordóñez et al., 2005; Tressol et al., 2008; Jacob and Winner, 2009; Weaver et al., 2009; Vieno et al., 2010). In particular, changes in climate affect air quality through modifications of ventilation rates, precipitation scavenging, dry deposition, chemical production and loss rates, natural emissions and background concentrations (Jacob and Winner, 2009). In addition, the higher frequency and intensity of extreme weather events also impact on atmospheric pollutant concentrations, though this impact is not quantified yet (Hong et al., 2019).

The IPCC 2018 report (IPCC, 2018) assessed that several regional changes in climate, including warming of extreme temperatures in many regions, intensity and/or amount of heavy precipitation and droughts in some regions under 1.5°C global warming with respect to pre-industrial levels.

To date, most studies have focused on the impact of temperature and other meteorological parameters such as relative humidity on O_3 and fine particle concentrations (Kinney, 2008; Madaniyazi et al., 2015). As reported in deliverable 1.4, temperature scenarios, coupled with precipitation pattern projections, suggest an increase in pollutants such as O_3 due to the increase in biogenic emissions and photochemical rates together with reduced wet removal. An increase in global temperatures will enhance photochemical reactions and the efficiency by which vegetation will produce VOCs (volatile organic compounds), the rate of atmospheric chemical reactions and the depth of the atmospheric boundary layer, all affecting surface pollutant concentrations (Heal et al., 2013). The general finding is indeed that global warming will shift O_3 production towards higher values in large urban areas, with an increase of 5-10% in the USA and Europe, particularly in polluted areas (Kinney, 2008; Jacob and Winner, 2009; Stowell et al., 2017). Conversely, the impact of climate change on PM is less clear, with a tendency of particulate mass to decrease with climate change but with little consensus on the results among the various studies conducted (e.g. Kinney, 2008; Tainio et al., 2013; Likhvar et al., 2015; Silva et al., 2016), with differences among the various component species (Kinney, 2008; Jacob and Winner, 2009), depending also on the complex coupling between PM and the hydrological cycle. Changes in meteorological variables can also modify sea level pressure patterns, with consequences on local circulation and distribution of air masses (deliverable 1.4).

In the iSCAPE project, the impact of future meteorology on air pollutant concentrations, considering only climate change induced modifications to meteorological variables without altering emissions (i.e. considering a "business-as-usual" scenario), was studied considering three cities that are representative of three different latitudinal bands in Europe, i.e. Bologna in southern Europe, Hasselt in central Europe, and Vantaa in northern Europe (deliverables 4.5 and 6.5). Results confirm the tendency for O_3 concentrations to increase across Europe in the future, with the largest increases in central Europe (10-30% over most of the city of Hasselt) followed by southern Europe (3-4%), while in northern Europe, where the highest warming is projected to occur in winter, O_3 concentrations may present more limited changes (Figure 22).

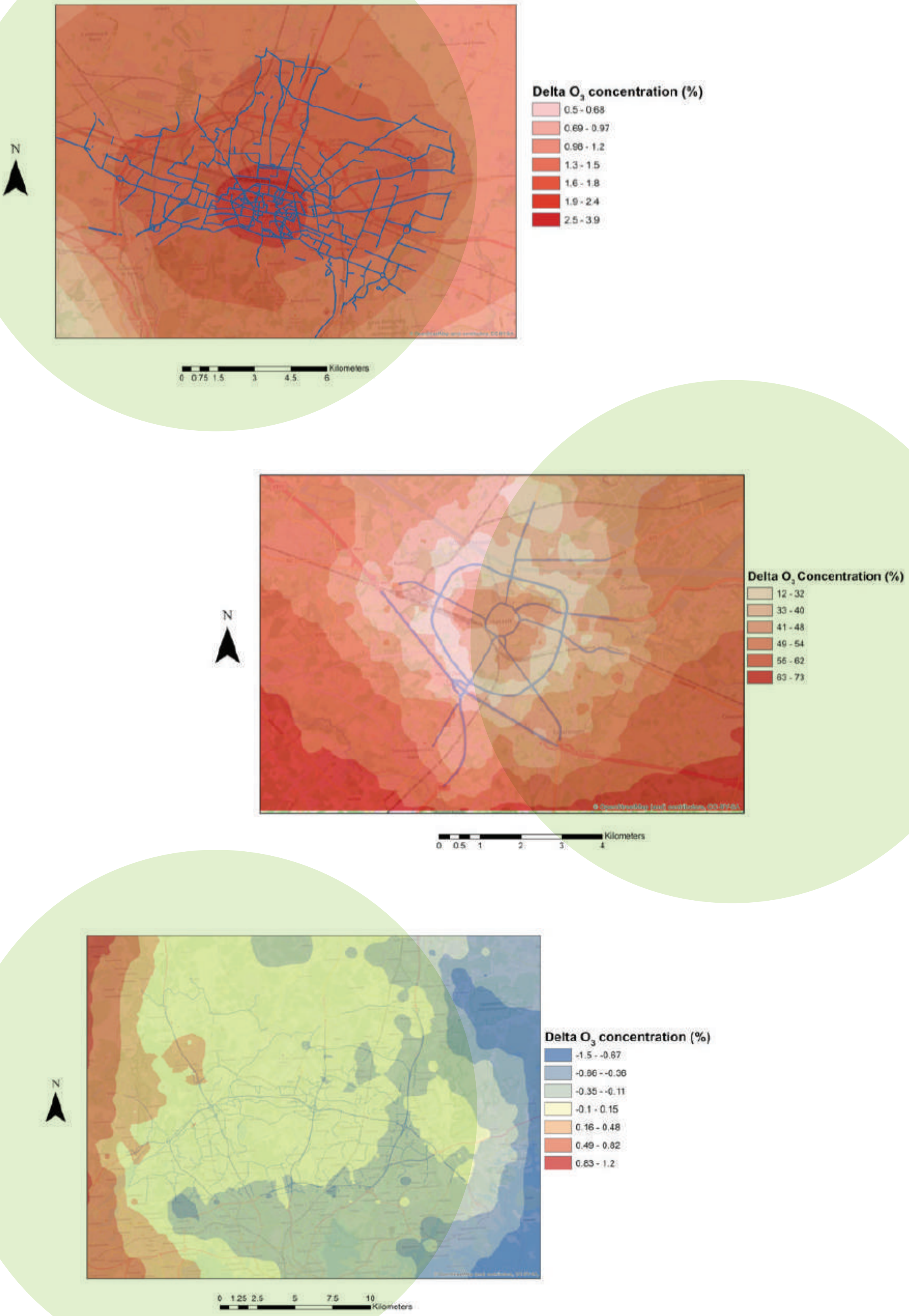
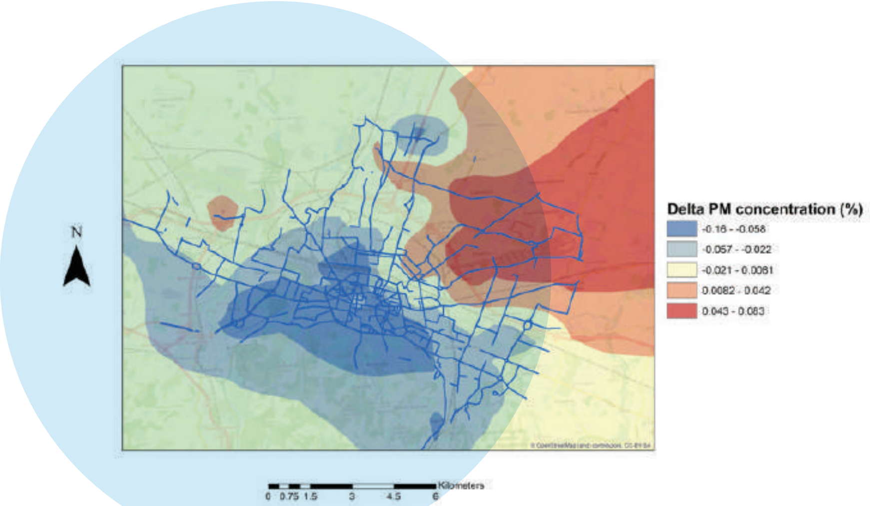
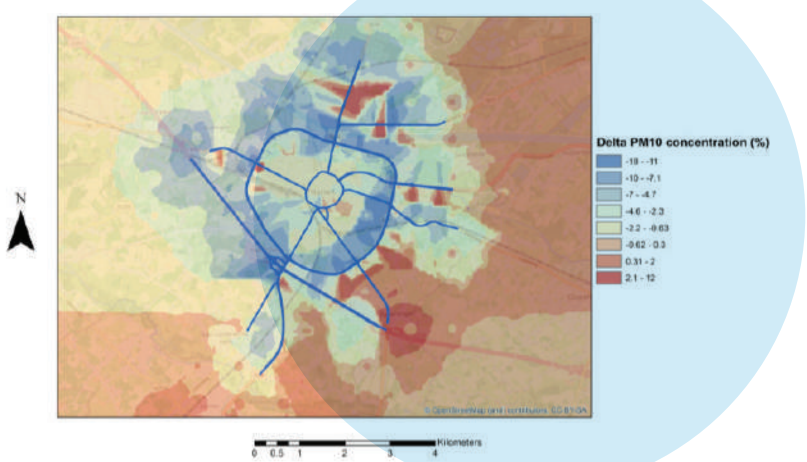


Figure 22. *Maps of changes in O_3 concentrations between a climate change future scenario and the current reference state over southern Europe (Bologna, top); central Europe (Hasselt, middle); northern Europe (Vantaa, bottom) (elaboration from results of deliverable 4.5).*

The largest changes in PM concentrations induced by the changes in meteorological conditions in a future climate are also observed in central Europe, with a tendency towards a decrease in concentrations over most of the domain (Figure 23). Limited changes are instead observed in southern and northern Europe, most likely driven by limited changes in wind speed and deposition patterns (deliverable 6.4).





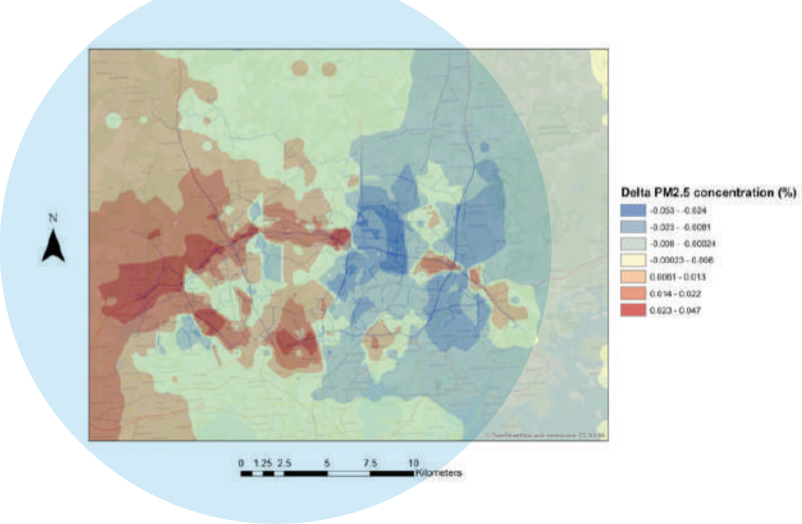


Figure 23. *Maps of changes in PM concentrations between a climate change future scenario and the current reference state over southern Europe (Bologna, top); central Europe (Hasselt, middle); northern Europe (Vantaa, bottom) (elaboration from results of deliverable 4.5).*

These changes further substantiate the need to counteract and mitigate climate change by reducing carbon emissions.

5.2 Air quality effects on climate change

In turn, many air pollutants impact upon the climate, contributing or modifying climate change through alterations of the amount, intensity and duration of sunlight that is reflected or absorbed by the atmosphere, with some pollutants exerting a warming and others exerting a cooling effect over the Earth. Short-lived climate forcing-pollutants (SLCPs) include methane (CH_4), tropospheric O_3 and aerosol components such as BC, sulphates and secondary organic aerosols. Through their absorption of terrestrial radiation, SLCPs such as BC and CH_4, but also tropospheric O_3, act like GHGs, and are among the top contributors to global warming after CO_2. As such, they can trigger and exacerbate climate change by altering the frequency, duration, and location of extreme events such as heat waves and cold spells, but also the storm intensity and precipitation patterns, with direct consequences for urban lives (Mitchell et al., 2016). Conversely, sulphates reflect solar short-wave radiation, thus exerting a cooling effect. Aerosols exert also indirect effects over climate, based on the ways in which they act as cloud condensation nuclei, in the formation of clouds. In particular, aerosols influence cloud microphysical processes and amount through changes in: 1) droplet concentration caused by increases in cloud condensation nuclei; 2) precipitation efficiency due to changes in droplet number concentrations (IPCC, 2013). While the direct effect of aerosols is well understood and contributes to counteract part of CO_2-induced global warming, the quantification of indirect effects represents one of the largest remaining uncertainties in climate change (IPCC, 2013).

The increase in tropospheric O_3 levels from pre-industrial to present day, driven by human activities and an increase in O_3 precursors, contributes a positive climate forcing (Fiore et al., 2012; IPCC, 2013) of +0.40 W m^{-2} as the best current specially considering that secondary inorganic aerosols (including sulphates) and carbonaceous aerosols make up the largest fraction of particulate mass (Putaud et al., 2004) but present radiative forcing of opposed signs. However, the findings generally indicate that climate change is intensified under the effect of enhanced pollutant emissions, which means that it will impact more on those regions highly affected by air pollution (deliverable 1.4).

The derivation of the forcing of NO_x is also rather complicated since increases in NO_x lead to increases in average tropospheric O_3 levels (warming effect), which may be offset by an accompanying cooling due to lower CH_4 concentrations in the presence of higher atmospheric oxidant capacity (Fiore et al., 2012). In addition, increasing NO_x may exert a further cooling effect by enhancing sulphate concentrations via increased oxidant levels (Fiore et al., 2012). In general, estimates of the effect of NO_x result in a cooling effect, with variabilities depending upon space and seasons (IPCC, 2013).

The simulations in a future business-as-usual scenario (Figure 24) indicate variable changes in NO_x concentrations with respect to present-day values, with increases over the city centre in southern Europe and decreases over the city centre in central Europe, while in northern Europe NO_x concentrations are predicted to vary little. Together with the difficulties and uncertainties previously indicated when estimating the net effect of NO_x on climate, these spatially-varying changes make it very hard to estimate the impact of air quality on climate change in the future.

Figure 24. *Maps of changes in NO_x concentrations between a future scenario under climate change and the current reference state over southern Europe (Bologna, top), central Europe (Hasselt, middle), and northern Europe (Vantaa, bottom) (elaboration from results of deliverable 4.5).*

5.3 Identification of episodes liaising air quality and climate change

As described in the previous sections, air quality and climate change are tightly linked, and every urban planning strategy must consider carefully both issues before being implemented. At present, policies to mitigate climate change and air pollution are often tackled in separate policy arenas and at different levels: for example, regional and local governments usually develop their own land-use decisions, while transport policies are a matter of national and transnational governments, even though separate plans are also set at the smaller city council and regional levels. However, due to various links between climate change, presenting a wide global impact, and air quality, the need to establish a link and collaboration between science and stakeholders from the local to the global point of view to develop and test the effect of policies for adapting and mitigating climate change and air pollution is becoming more and more evident.

In the following, we present some episodes clearly liaising air quality and climate change.

First of all, undoubtedly, the August 2003 heat wave, during which record-high O_3 concentrations were observed all over Europe (e.g. Solberg et al., 2003; Filleul et al., 2006; Pellegrini et al., 2007; Vieno et al., 2010). Similar O_3 peaks were recorded during the European June and July 2019 heat waves (Chazan, 2019; Barry and Cecereda, 2019). Attribution studies have found a direct contribution of climate change in 2019, 2018, 2017, 2015, 2010, 2003, 2016, and 2002 European heat waves (Vautard et al., 2019). Additionally, during those heat waves, Europe was swept by strong, hot winds from Africa, which transported high concentrations of PM (see Figure 25).

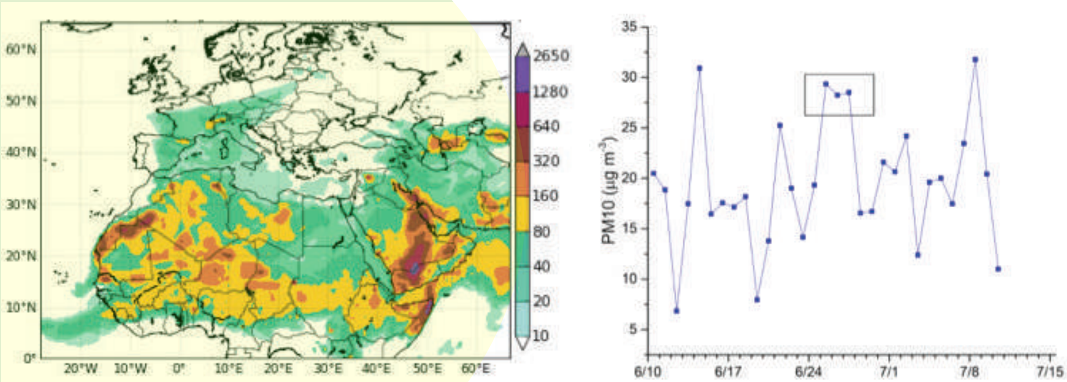


Figure 25. *(left) Dust surface concentration over northern Africa and southern Europe on 27 June 2019 at 12:00 UTC (image courtesy of the NMMB/BSC-Dust or BSC-DREAM8b) model, operated by the Barcelona Supercomputing Centre (http://www.bsc.es/ess/bsc-dust-daily-forecast/)". (right) PM_{10} concentration pattern during June-July 2019 monitored in Bologna in southern Europe. The 26-28 June 2019 period with increases in PM_{10} concentration is highlighted in the black rectangle.*

The long-term decline in the zonal-mean zonal wind, implying a weakening of the summer circulation at mid-latitudes and the higher persistence of hot weather (Coumou et al., 2015), is also linked to an increase in stagnation events, generally predicted to be more frequent because of anthropogenically enhanced climate change (Horton et al., 2012). It is recognized that blocking high-pressure systems create stagnant weather conditions for air pollution episodes.

For example, in December 2016, western European weather was dominated by persistent anticyclonic conditions leading to dry and calm weather resulting in accumulation of air pollutants (Vautard et al., 2016). PM_{10} concentrations reached elevated levels over the main air pollution hotspots in Europe, i.e. the Po-Valley, eastern Europe, and Benelux (Vautard et al., 2016). Very low wind speeds were also observed in the same period over western Europe, a condition which is typical of stagnant weather conditions (Vautard et al., 2016).

As reported in deliverable 6.1, stagnant weather conditions often adversely affect those pollution hotspots, which includes Bologna in the Po-Valley (southern Europe) region. An example of stagnant weather was analysed in deliverable 5.2, where a connection was shown between low boundary layer height limiting dispersion and high NO_x concentrations in Bologna during the morning of 31 January 2018 (Figure 26).

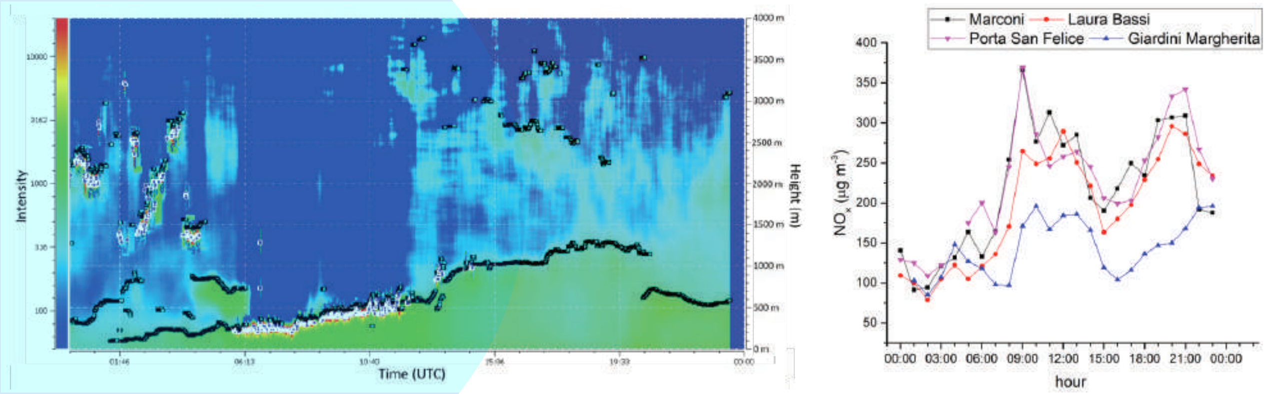


Figure 26. *Diurnal cycle of boundary layer height (top) and* NO_x *hourly means concentrations measured in various air quality stations (bottom) in Bologna on 31/01/2018 (source: deliverable 5.2 update).*

5.4 Recommendations for episodes identification

As mentioned previously, the interactions between meteorological variables and the transport, formation, chemical transformations, dispersion and deposition of pollutants are various and complex. Focusing on local dispersion and accumulation dynamics, air ventilation indices to quantify the capability of the atmosphere to disperse air pollution usually take into account basic meteorological variables such as daily total precipitation and wind speed. In particular, the most used Air Stagnation Index is constructed as (Garrido-Perez et al., 2018):

- *daily total precipitation less than 1.0 mm (i.e., dry days)*
- *daily mean wind speed at 10 m lower than 3.2 ms*$^{-1}$
- *500 hPa wind speed below 13.0 ms*$^{-1}$

Besides these two variables, the analysis of air temperature, solar radiation and relative humidity levels are also especially important because of their effects on chemical reactions rates, O_3 levels and atmospheric oxidant capacity.

After that, when an episode of high air pollution in connection with extreme events such as a heat wave is found, it is necessary to attribute it to climate change which is not straightforward and the support from climate change analysts is needed. In general, however, to attribute an event to climate change it is necessary to compute the change in likelihood of the events under interest (such as heat waves, droughts and heavy precipitation events) in a climate with and without anthropogenic forcing (e.g. Kew et al., 2019; Vogel et al., 2019).

Based on the previously mentioned difficulties and complexities inherent in the multiple connections between air quality and climate change, a close collaboration is recommended between stakeholders and scientific experts of various disciplines, such as climate change, meteorology, air pollution.

5.5 Action plans to consider air quality-climate change interactions

A city is a dynamic and complex system, especially in times of climate change. Urban systems can promote this change but are also exposed to it. The answer of urban development planning is to take measures against the causes (e.g. reduction of air pollution, especially GHGs) and impacts of climate change (e.g. reduction of the UHI effect) without the measures interfering with each other. The unpredictability of climate change, its multiple causes, impact chains and interactions in the complex system of a city call for a forward-looking and coordinated integrated urban development approach. Such an integrated approach contributes to avoiding conflicts of objectives regarding the reduction of air pollution and the UHI effect, as well as other urban issues such as economic growth or long-term changes in demography, technology and social behaviour (Walsh et al. 2011).

An action plan, as an informal policy tool, is a strategic instrument that is not bound by planning law and can be tailored to the needs and demands of an affected city. It provides a clear and systematic framework and offers planners as well as other local decision-makers an orientation for the complex and demanding task of developing, implementing and reviewing strategies for dealing with the consequences of climate and environmental impacts. This instrument describes the problem and the need for action, defines goals to be achieved, sets priorities, and bundles existing or new interventions to achieve these goals (Tang et al. 2010). It also contains the elements of monitoring, evaluation and communication. An action plan is developed in a participatory manner and by involving various experts and non-state stakeholders (Tang et al. 2010). With the adoption of an action plan, the stakeholders publicly express their political will to implement the adopted interventions within a certain period of time.

For developing an integrated action plan and portfolio of effective urban level interventions options, a better understanding of impact chains and interactions is crucial. Complex impact chains and interactions need to be made more tangible by deconstructing them based on spatial and temporal scales (Walsh et al. 2011). Whenever one challenge is addressed through an intervention/measure, the relevant interdependencies need to be taken into account in order to identify, at best, synergies, and to tackle challenges simultaneously (Walsh et al. 2011). Due to the complexity of this task, general effective decision-making remains challenging and can be restricted if it attempts to consider and weigh all alternatives at the same time. Nevertheless, these insights have to be regarded in an integrated way when it comes to decision-making.

For the development of an action plan as part of iSCAPE, we built on the co-creation of the Bottrop and Hasselt LLs, which are both created on urban level. For example, in Bottrop, we conducted workshops with an interdisciplinary team in which we carried out a joint and integrated evaluation of measures and qualitatively weighed the best-rated measures with regard to their possible interactions and side effects (see deliverable 3.9, Report on potentialities of urban interventions and action plans). This approach allows the tailor-made selection and prioritisation of measures while focusing on interactions within the complex urban system.

In order to develop and implement action plans effectively, a number of conditions need to be met. These conditions are addressed to different stakeholder groups, which play an essential role in the development and implementation processes. As the example of the Bottrop LL shows, it requires good cooperation and networking between different departments of an administration to ensure the exchange of disciplinary information. Apart from that, the support of political decision-makers is also of great importance since their agreement is the linchpin to implement an action plan. In addition, the involvement of and acceptance by citizens concerning the objectives and measures integrated into the plan is required. It enhances the implementability as several measures are up to private households.

Beyond transdisciplinary cooperation and political support, further success factors of developing and implementing an action plan are as follows:

- *An accompanying sustainable implementation strategy (mainstreaming or dedicated strategy).*
- *Integration of measures into existing implementation instruments and tools (at best a combination of legally binding planning instruments as well as informal and more flexible planning instruments).*
- *Monitoring and evaluation, since an action plan is dynamic and flexible in terms of adjustments to changing framework conditions.*
- *Personnel resources, financing or subsidies.*

6. Recommendations for Passive Control Systems

6.1 Green infrastructure

GI includes all green species such as trees, hedges, individual shrubs, green walls, and green roofs/walls. GI offers many different benefits or services, including flood risk management, microclimate regulation, carbon sequestration, improved health and wellbeing, reduce heat stress and mitigate air pollution at different urban scales. Air pollution comprises variable quantities of many different types of pollutants, including gaseous pollutants, such as NO_x, and PM, which is a complex mixture of extremely small particles and droplets, with variable chemical composition but ubiquitarily mainly constituted by secondary inorganic (sulphates, nitrates, and ammonium) and carbonaceous aerosols, including BC. Road traffic is a dominant source of air pollution in urban areas globally. As reported previously, in near-road environments, vegetation can act as a barrier between traffic emissions and pedestrians, by collecting pollutants and/or redirecting the flow of polluted air.

This section summarises best practice regarding GI implementation for improved urban air quality and hence reduction in human exposure to air pollution. Generic (i.e. not site-specific) recommendations are offered for typical urban environments. These recommendations are based upon current scientific evidence and knowledge, and may therefore be subject to modification as the evidence base develops. This guidance document consolidates major findings from relevant publications, including a detailed report on the relationship between vegetation and urban air quality (DEFRA, 2018), review articles (Abhijith et al., 2017; Barwise and Kumar, under review) and other guidance documents (Ferranti et al., 2019). Furthermore, this document complements a recent report commissioned by the mayor of London (Greater London Authority, 2019), which included inputs from the Global Centre for Clean Air Research, University of Surrey, and extends beyond its scope by offering recommendations on plant selection and vegetation management that appeared as an iSCAPE output in Kumar et al. (2019b).

6.1.1 General design recommendations

The recommendations given in Table 1 are relevant to GI implementation in both street canyon and open-road environments, which are described in subsequent sections.

Seasonal effects	Evergreen species are generally recommended for continuous impact over the course of the year and because air pollution concentrations can be worse in wintertime (see Table 10 for UK cities).
Leaf surface	The chosen vegetation should have complex, waxy (e.g. Juniperus chinensis) and/or hairy (e.g. Sorbus intermedia) leaf surfaces, with a high surface area (i.e. small and/or complex leaves). These features assist in the deposition and removal of particulate pollutants.
Non-invasive	It is important to select non-invasive species to protect existing ecosystems.
Non-poisonous	When planting near sensitive populations (such as school children), it is important to avoid species that are poisonous or those that may cause allergic reactions.
Road safety	GI design should be managed to meet applicable safety regulations for the visibility of drivers, cyclists or pedestrians. Similarly, GI should not impede accessibility where relevant.
Existing infrastructure	Site selection for planting should give due consideration to existing infrastructure, such as utilities (gas, water, electricity), the cost of disruption to which may be a barrier to successful implementation.

Table 1. *General recommendations on GI selection for both street canyon and open-road conditions (Kumar et al., 2019b).*

6.1.2 General management considerations

Appropriate GI can be used to mitigate air pollution. However, the management of vegetation can itself be a source of emissions, not only through the equipment used but through biogenic volatile organic compound (bVOC) emissions from the vegetation, which increase when a tree is 'wounded' (e.g. pruned). In order to minimise any potential trade-offs between the air quality benefits offered by urban vegetation and the potential costs (both monetary and environmental) associated with establishment and maintenance, it is important to consider the long-term suitability of a species to the planting site. Working with nature or understanding and playing to the natural tendencies of individual species, will optimise success rates in establishment and performance. This, in turn, will minimise costs associated with management (e.g. re-planting and aftercare, including weeding and pruning). Unfortunately, it is not possible to create a thorough list of low-maintenance species, for two primary reasons. Firstly, the incalculable range of potential environmental conditions means that different species will be suitable (and therefore require less maintenance) for different sites. Secondly, different objectives necessarily entail different ideal growth forms (it would, for example, be inefficient to maintain a fast-growing species as a low hedge or to maintain a slow-growing species until it becomes an effective shelterbelt). With this in mind, Table 2 provides a summary of key points to consider.

Management consideration	Description
Air pollution tolerance	Species should be tolerant of air pollution in order to remain healthy and effective in mitigating it. Observed tolerance (rather than proven via experimentation) may be sufficient. However, air pollution tolerance should be considered alongside any trade-offs (for example, a species may be highly tolerant but emit high amounts of allergenic pollen).
Growth shape (morphology)	Species should be selected on a site-by-site basis and with their projected growth form in mind. In a shallow street canyon, for example, a medium-sized and lighter-crowned species may be suitable, whereas in a deep street canyon, a naturally compact tree or shrub may be more appropriate.
Tolerance of other typical urban stresses	The chosen species should be suitable for the specific conditions of the site, which may include, for example: salt spray (for winter road conditioning), drought, root compaction, flooding, waterlogging, or shade.
Succession*	Consideration of a species' successional stage under open forest conditions can help to indicate the type of environment in which it may thrive. As a simplified example: early-successional (or 'pioneer') species, such as Betula spp., tend to cope well under-exposed and windy conditions, whereas late-successional (or 'climax canopy') species, such as Quercus spp., tend to be shade-tolerant.

*Succession describes the process or system of natural change in the species structure of an ecological community (e.g. an area of woodland) over time. This process is generally predictable for a given community and includes the order in which certain species tend to become established.

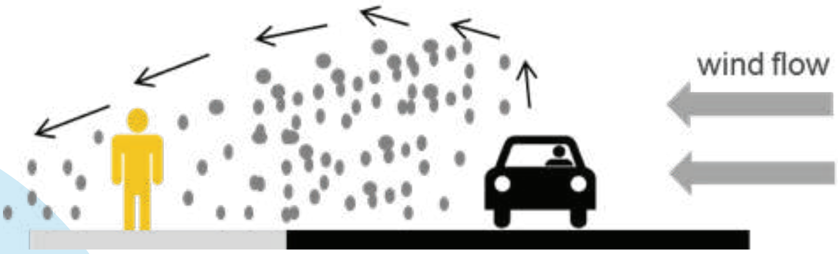
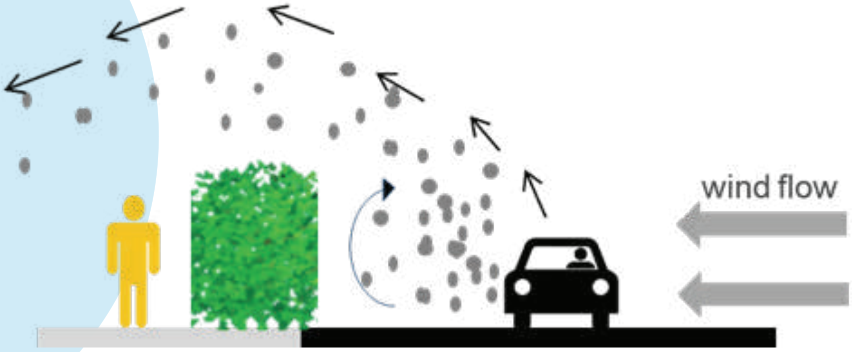
Table 2. *Considerations for effective GI management regarding species selection (Kumar et al., 2019b).*

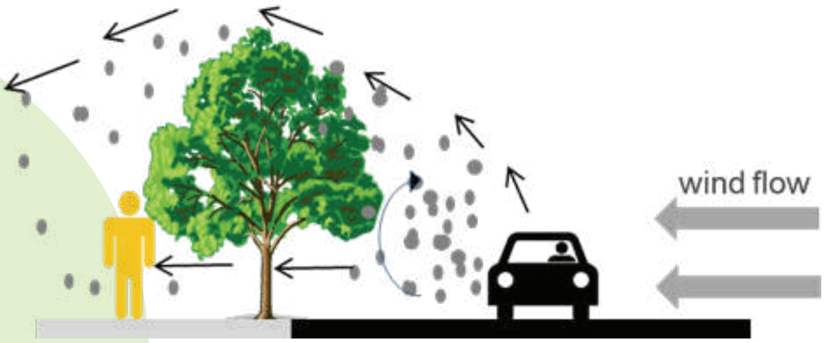
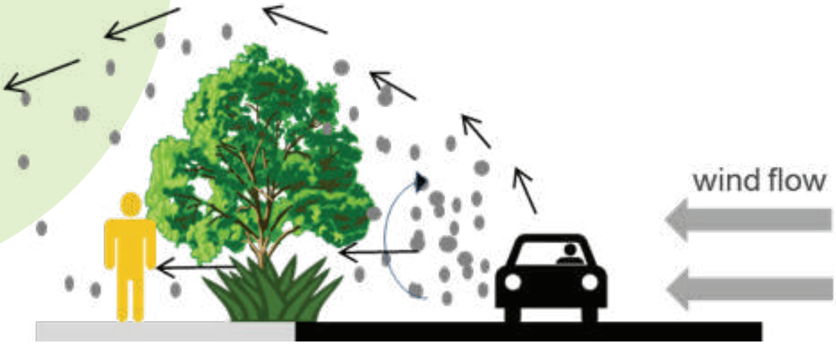
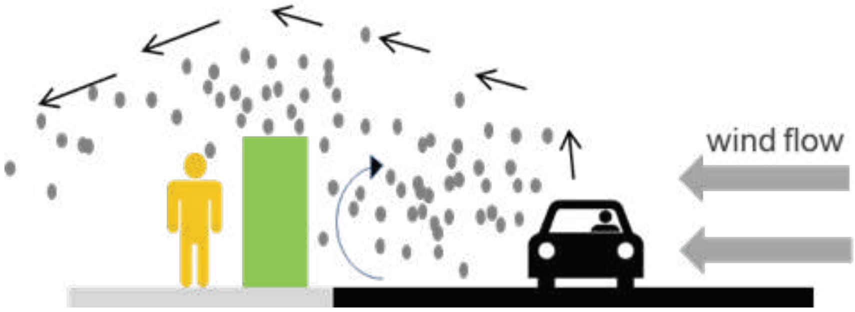
In urban areas that may often be subject to temperatures above 20°C, species that are high-emitters of bVOCs should be avoided, particularly for large-scale planting schemes. Such genera include *Quercus*, *Populus*, *Salix*, and *Picea*. Similarly, the assumed air quality benefits of introduced vegetation may be nullified if the chosen species releases high amounts of allergenic pollen during the flowering period. Where sensitive human populations coincide (for example, near schools and hospitals), insect-pollinated species or female varieties of dioecious species are recommended (Ogren, 2015).

6.1.3 Open-road environments

Open-road conditions describe a road that is either away from buildings or where nearby buildings are generally detached. Here, wind flows are less hindered or influenced by buildings and other structures when compared with street canyon environments.

In open-road environments, trees and other vegetation are often planted or occur naturally along one or both sides of the road. These forms of GI may be relatively broad areas of woodland or other vegetation or may simply entail roadside hedges. They provide a natural barrier against emissions from the road, potentially reducing exposure levels for those travelling, working or residing adjacent to such roads. Comparison of different types of open-road environments with and without GI are illustrated in Table 3.

Open-road conditions	Simplified diagram
Open-road with no vegetation barriers between traffic emissions and pedestrians.	
Open-road with a hedge acting as a barrier between traffic emissions and pedestrians.	

Open-road with trees acting as a filter between traffic emissions and pedestrians.*	
Open-road with combined vegetation barriers between traffic emissions and pedestrians.	
Open-road with a green wall acting as a barrier between traffic emissions and pedestrians.	

*Under some conditions, due to a windbreak effect, pollutants can stagnate behind a sparse row of trees, leading to deteriorated downwind air quality (Abhijith and Kumar, 2019).

Table 3. *A simple description of open-road conditions and pollution flow (Kumar et al., 2019b).*

The suggested design parameters and considerations regarding GI configuration in open-road environments are summarised as follows (Table 4):

Design parameter	Considerations
Location	Hedgerows should be planted between the road and walkways or dwellings and in front of trees (if present); this configuration offers the maximum reduction of exposure.
Spacing	Barriers with no gaps both along cross-sectional and longitudinal directions provide better downwind exposure reduction.
Height	Where possible, it is recommended that the combined hedge-tree barrier or the green wall has a height of 5 m or more. Vegetation barriers with greater height result in increased pedestrian-side pollutant reductions. A minimum height of 1.5 m is recommended.
Thickness	The vegetation should be as thick as possible; thicker vegetation barriers offer greater exposure reduction. If possible, a thickness of more than 5 m is recommended.
Density	High-density vegetation barriers are generally better for reducing exposure levels downwind/pedestrian-side.

Table 4. *Considerations for open-road GI (Kumar et al., 2019b).*

The recommendations based on the measured five parameters in front of and behind a hedge over a three months period using low-cost sensors are:

- *The largest air pollution reduction by vegetation is achieved when placing vegetation next to the busiest roads and roads with a consistently high volume of traffic.*
- *Evergreen hedges are preferred to deciduous hedges, since these are not expected to change with the vegetation cycle.*
- *Hedges are recommended as an air pollution mitigation strategy in areas strongly influenced by PM pollution since they will be less effective for gaseous pollutants.*
- *When all the previous recommendations have been taken into account, the dominating wind direction can be taken into account as well.*
- *More research is required to be able to quantify the air pollution reduction by hedges for all conditions (e.g. vegetation geometry, species, etc.).*

Summary of recommendations for GI implementation in open-road conditions are shown as a coloured matrix in Table 5.

Open-road	Hedge	Tree	Green wall	Combination of trees and hedges
Overall usability	Best	Good	Good	Best
Height	> 5 m Best	> 5 m Good	Good	Best
Thickness	> 10 m Best	> 10 m Good	Good	Best
Spacing (Yes/No)	No Best	No Good	No Good	Best
Density (High/Low)	High Best	High Good	High Good	Best

Table 5. *Matrix of GI design for open-road condition.*

Good Best

6.1.4 Street canyons

When considering air quality and pollutant dispersion, street canyons are a complex urban feature, as shown in Figure 27.

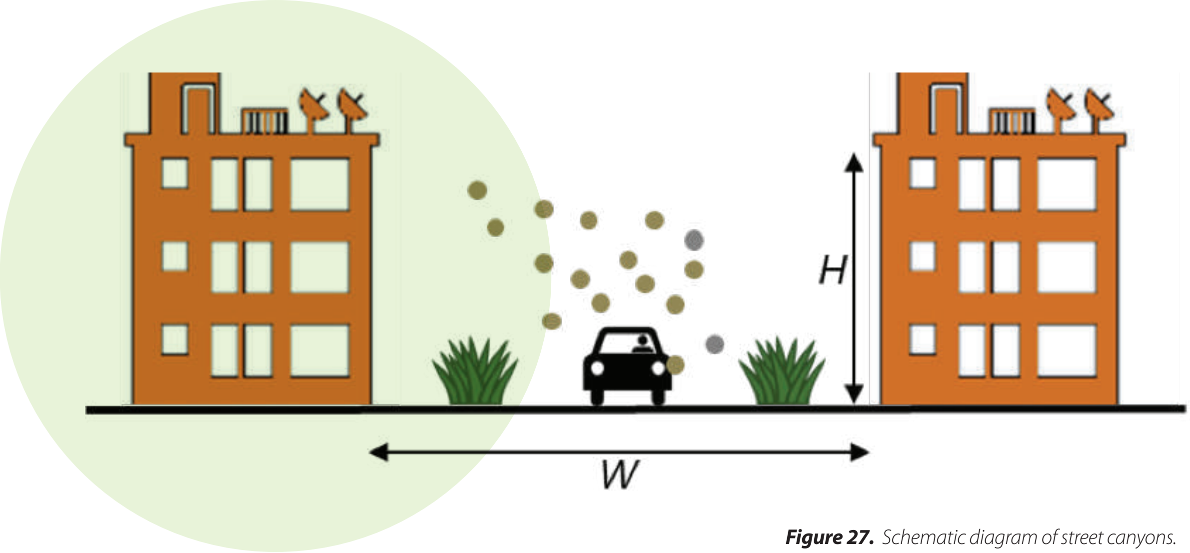


Figure 27. *Schematic diagram of street canyons.*

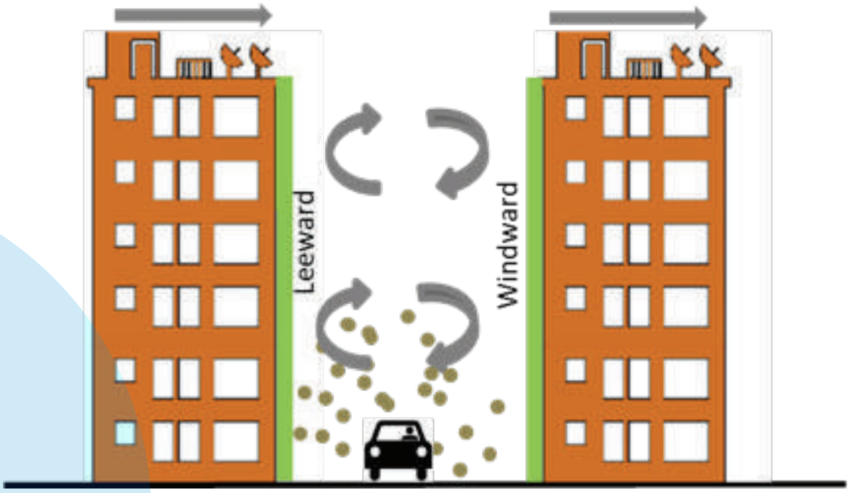
H is the height of the buildings and W is the horizontal distance between the buildings. The ratio of H to W is called the aspect ratio, which significantly affects pollutant dispersion patterns. For simplicity, street canyons can be defined according to their aspect ratio.

$H/W \geq 2$ = deep or narrow street canyons

$0.5 < H/W < 2$ = moderately deep street canyons

$H/W \leq 0.5$ = shallow or wide street canyons

Deep street canyons can experience increased pollutant concentrations regardless of the presence of vegetation, due to limited air exchange between polluted air within the canyon and fresh air outside it. The presence of large trees in street canyons can result in a deterioration of overall air quality, by trapping pollution at ground-level. This does not mean that existing trees should be cut down, because they offer ecosystem services beyond air quality support, but that due caution should be undertaken in considering appropriate species for new planting. The general recommendations are listed in Tables 6 and 7.

Street canyon aspect ratio	**Sketch** (wind direction roughly perpendicular to the street)
H/W ≥ 2 (deep or narrow street canyons) Recommended: ○ Trees - No ○ Hedges - No ○ Green walls - Yes	
0.5 < H/W < 2 (moderately deep (nearly regular; i.e. w~=h) street canyons) Recommended: ○ Trees - No ○ Hedges - No ○ Green walls - Yes	

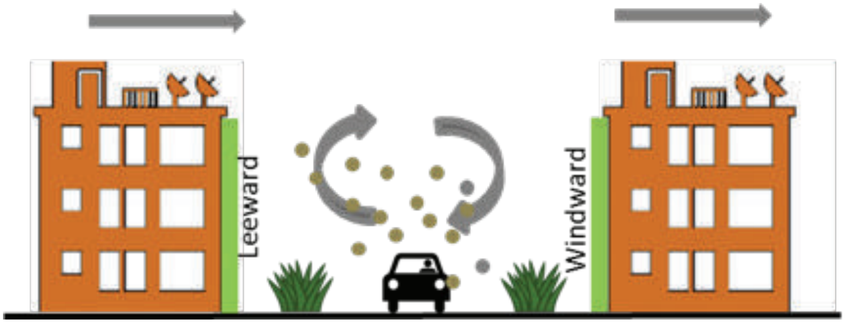
Street canyon aspect ratio	Sketch (wind direction roughly perpendicular to the street)
H/W ≤ 0.5 (shallow or wide street canyons) Recommended: ○ Trees - Conditionally (small, lighter-crowned species, preferably planted only on the windward side) ○ Hedges - Yes ○ Green walls - Yes	

Table 6. *General recommendations for different aspect ratios (Kumar et al., 2019b).*

Design parameter	Considerations
Location	If the prime objective is to reduce exposure for pedestrians or cyclists, hedges should be planted close to the road, between the road and footpath/bike path. Green walls can be constructed on the pillars of flyovers, retaining walls and other boundary walls.
Selection of vegetation	In deep street canyons, no forms of vegetation except green walls are recommended. In mid-depth street canyons, shrubs or hedges and green walls can be planted, but trees are not recommended. Large, dense trees should be avoided in all street canyons, but smaller or lighter-crowned trees may be planted in shallow street canyons.
Spacing	Continuous hedges (with no gaps or spacing) provide a better reduction in exposure for pedestrians and cyclists. If trees are to be planted (shallow canyons only), they should be spaced generously apart from one another.
Height	For hedges, a height of around 2 m is recommended.
Thickness	For hedges, a thickness of 1.5 m or more is recommended.
LAD	In street canyons, a higher density for hedges and lower density for trees is generally recommended.

Table 7. *Generic features for street canyons (Kumar et al., 2019b).*

A summary of the recommendations for GI implementation in street canyon conditions is shown as a coloured matrix in Table 8 below. The colour guidelines are shown in Table 9.

Street canyon		Hedge	Tree	Green wall	Green roof
Overall usability		🟢	🔴	🟢	🟩
Aspect ratio	H/W ≥ 2 (narrow)	🔴	🔴	🟩	🟩
	0.5 < H/W < 2 (in-between)	🟠	🔴	🟢	🟢
	H/W ≤ 0.5 (wide)	🟩	🟠	🟢	🟢
	Windward	🟢	🟩	🟢	🔵
Location	Leeward	🟩	🔴	🟩	🔵
Height	-	🟢 2 m	⚪	⚪	🔵
Thickness	-	🟢 1.5 m	⚪	⚪	⚪
Spacing	Yes or No	🟢 No	🟢 Yes	🟩 No	⚪
Density	High or low	🟢 High	🟩 Low	🟩 High	⚪

Note. *H = Height of canyon walls; W = width of canyon walls*

Table 8. *Matrix of GI design for street canyons.*

Not recommended	🔴	**Best**	🟢	**Not good/ maybe**	🟠
Not applicable	🔵	**Good**	🟩	**No/less evidence**	⚪

Table 9. *Colour index for recommendation for GI plants.*

6.1.5 Potentially effective species

The woody plant species in Table 10 are identified as potentially advantageous for air pollution abatement. This table was constructed with UK environmental conditions in mind (e.g. regarding native, naturalised, or non-native status), although a majority of the noted species may be viable for planting across Europe, subject to site-specific assessment. Similarly, it should be noted that this list is not exhaustive, and is offered instead as a starting point in species selection and an outline of points to consider with respect to the context of the planting site. For brevity, the table explicitly and solely reflects aspects of species that relate to air quality. The suitability of each species to the environmental conditions of the planting site is paramount.

Tree species	Type	Air pollution tolerance	bVOCs	Pollen	Canopy density	Comments	Image
Scots pine (Pinus sylvestris)	Evergreen conifer	Observed/proven	Low	Low	Moderate	Early successional; native; good drought tolerance	
Stone pine (Pinus pinea)	Evergreen conifer	Observed/proven	Low	Low	Dense	Non-native; a more compact option than P. sylvestris; good drought tolerance	
Himalayan cedar (Cedrus deodara)	Evergreen conifer	Unknown/unproven	Low	Low	Dense	Non-native; potentially a massive, broad tree; very good drought tolerance	
Swedish whitebeam (Sorbus intermedia)	Deciduous broadleaf	Observed/proven	Low	Low	Moderate	Naturalised in UK; known salt tolerance; some tolerance to drought; leaf undersides are hairy	
Ulmus 'Rebella'	Deciduous broadleaf	Observed/proven	Unknown	Low	Moderate	Non-native; medium-sized tree; resistant to Dutch elm disease; good drought and salt tolerance	
Wild cherry (Prunus avium)	Deciduous	Observed/proven	Low	Low	Moderate	Early successional; native; good drought and salt tolerance	
Callery pear (Pyrus calleryana)	Deciduous broadleaf	Observed/proven	Low	Low	Dense	Non-native; proven viability for paved environments; good drought and salt tolerance	
Staghorn sumac (Rhus typhina)	Deciduous broadleaf	Observed/proven	Low	Low	Moderate	Early successional; non-native; small- to medium-sized tree; good drought and salt tolerance	
False acacia (Robinia peudoacacia)	Deciduous broadleaf	Observed/proven	Low	Low	Open	Early successional; non-native; potentially a large tree; good drought and salt tolerance; can be invasive	
Common hackberry (Celtis occidentalis)	Deciduous broadleaf	Observed/proven	Low	Low	Moderate	Early successional; non-native; massive tree; some observed drought and salt tolerance	

Tree species	Type	Air pollution tolerance	bVOCs	Pollen	Canopy density	Comments	Image
Leyland cypress (x Cuprocyparis leylandii)	Evergreen conifer	Unknown/unproven	Low	Low	Dense	Non-native; very fast-growing, and potentially very large; good drought and salt tolerance	
Common yew (Taxus baccata)	Evergreen conifer	Observed/proven	Low	High, but dioecious	Dense	Late successional; native; versatile hedging plant, can be trained to form a barrier of any shape; good	
Box (Buxus sempervirens)	Evergreen broadleaf	Unknown/unproven	Low	Low	Dense	Native to southern England; a low-branching tree with the dense canopy; good drought tolerance	
Western red cedar (Thuja plicata)	Evergreen conifer	Observed/proven	Low	High	Dense	Late successional; on-native; good, dense hedging plant for a tall barrier; good drought tolerance	
Chinese juniper (Juniperus chinensis)	Evergreen conifer	Observed/proven	Low	High, but can be dioecious	Dense	Early-successional; non-native; good drought tolerance	
Field maple (Acer campestre)	Deciduous broadleaf	Observed/proven	Low	Low	Dense	Early successional; native; good drought and salt tolerance	
Amur maple (Acer tataricum subsp. ginnala)	Deciduous broadleaf	Observed/proven	Low	Low	Dense	Late successional; non-native; good drought and salt tolerance; ornamental autumn colour	
Downey serviceberry (Amelanchier arborea)	Deciduous broadleaf	Observed/proven	Low	Low	Moderate	Non-native; some observed salt tolerance; moderately sensitive to drought; ornamental autumn colour	
Common hawthorn (Crataegus monogyna)	Deciduous broadleaf	Observed/proven	Low	Low	Dense	Early successional; native; good drought and salt tolerance	

Table 10. *Woody plant species that are considered to be potentially effective for air pollution abatement in UK cities, based either upon experimental findings, an exhibition of beneficial traits, or a combination of both (Kumar et al., 2019b). Note: Site-specific management should include consideration of invasive species that may perturb existing ecosystems, which this table does not consider.*

6.1.6 City environment

Urban air quality

For urban air quality, the most important forms of GI are street trees, roadside hedges, green walls and roofs, parks, urban forests and grasslands adjacent to the urban boundary, where air exchange is significant. In urban environments, these GIs can reduce pollutant concentrations by offering a greater surface area, which increases dry deposition, enhances pollutant redistribution and increases atmospheric turbulence. However, some GI characteristics can strengthen atmospheric stagnation and increase local air pollution concentrations. Earlier studies have also suggested the positive impact of GI in UHI mitigation, reductions in noise pollution, storm water management, and the consideration of GI as a part of natural capital. The general recommendations related to urban planning are listed below:

- Evergreen, coniferous trees should be planted near traffic lanes (or around pollutant sources) to harvest their maximum potential in terms of pollutant removal.
- Evergreen trees with high LAD may be planted as hedges near traffic lanes to confine the air pollutant within GI canopy.
- For GI urban planning at city scale, the selected species should exhibit low bVOCs emissions.
- To avoid short episodes of high bVOC concentrations, GI in urban environments should account for different bVOC emission periods.
- Green roofs may be opted as additional passive sinks to remove air pollutants and also help to manage runoff water quantity.

Urban heat island

In spite of the increasing amount of research in UHI mitigation by GI, the understanding of the effects of different forms of GI remains fragmented and the level of utilisation by urban planners is low. Thus, we have presented some recommendations for UHI mitigation and reduced urban temperatures. The recommendations (Kalaiarasan et al., in preparation) are:

- An optimal arrangement of GI in a street canyon or wider landscape in urban areas will mitigate high urban temperatures.
- Implementation of green roofs will increase the albedo and enhance the emissivity of solar radiation, causing a reduction in absorption and emission of heat from urban fabrics and improve air quality and urban biodiversity.
- GI types with higher shading and cooling potential should be implemented for greater UHI mitigation.

- The percentage of GI (trees, grasslands, hedges and other types of GI) should be equal to obtain an optimal rate of mitigation.
- The LAD of trees or any other GI type is an important factor and evergreen GI is recommended for UHI mitigation.
- Reduced energy usage for cooling in buildings should be implemented by planning proper ventilation systems that will reduce the anthropogenic heat emissions from the buildings.

6.2 Low boundary walls

LBWs can be used to reduce air pollution and improve air quality at footpaths in street canyons by increasing localized dispersion. Based on previous studies, it has been noted that installation of LBWs near the footpaths (Figures 28 and 29) has the potential to improve air quality to pedestrians by reducing pollutants such as NO_x and PM ($PM_{2.5}$ and PM_{10}).

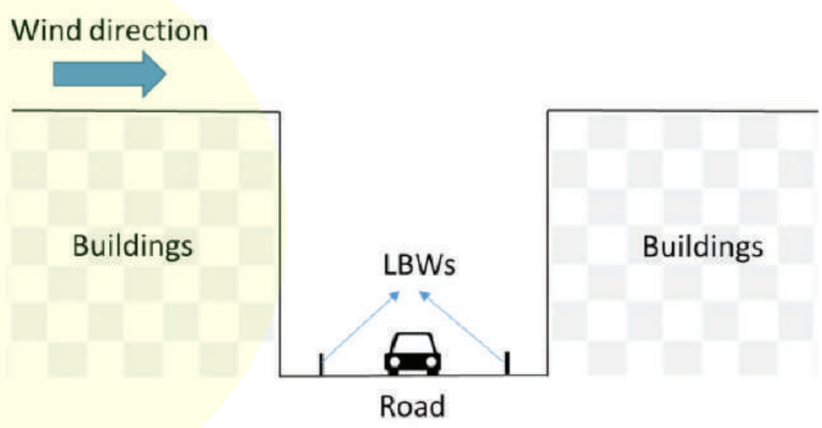


Figure 28. *Schematic diagram of street canyons with LBWs.*

Figure 29. *Image of street canyon along with LBWs.*

6.2.1 General design recommendations

The recommendations given in Table 11 are relevant to implementation of LBWs in real-world street canyon to improve air quality for the pedestrians.

Continuity	In order to achieve maximum efficiency in reducing air pollution for pedestrians, the LBWs should be as continuous as possible.
Accessibility	Gaps in the LBWs needs to be provided at the junctions of roads, near bus stops, buildings and schools to ensure accessibility.
Road safety	The height of LBWs should be within a certain range (0.5-1 m) to ensure visibility of drivers, cyclists and pedestrians.
Flexibility and Durability	In certain circumstances it might be necessary to remove the LBWs to increase accessibility inside the canyon. Hence the LBWs should be made of materials that are light-weight and easily transferable, such as tarpaulin sheets. As the strength of those materials are less when compared to concrete walls, it is necessary to ensure that the LBWs are properly installed and they do not get displaced due to factors such as high wind.
Performance	It has been noted that LBWs can reduce air pollution at certain sections of the road and footpath, but can have a reverse effect in some other sections of the street canyon. The location of the LBWs should be selected in such a way that the air pollution reduces in important locations of the street such as schools and office/building entrances, even though the pollution can increase at certain other unimportant locations.

Table 11. *General recommendations on selection of LBWs implementation in a real world street canyon to improve air quality.*

6.3 Photocatalytic coatings

Photocatalytic coatings include a wide variety of titanium oxides (TiO_2). The following figure (Figure 30) resumes the main raw and processed materials used in practical applications.

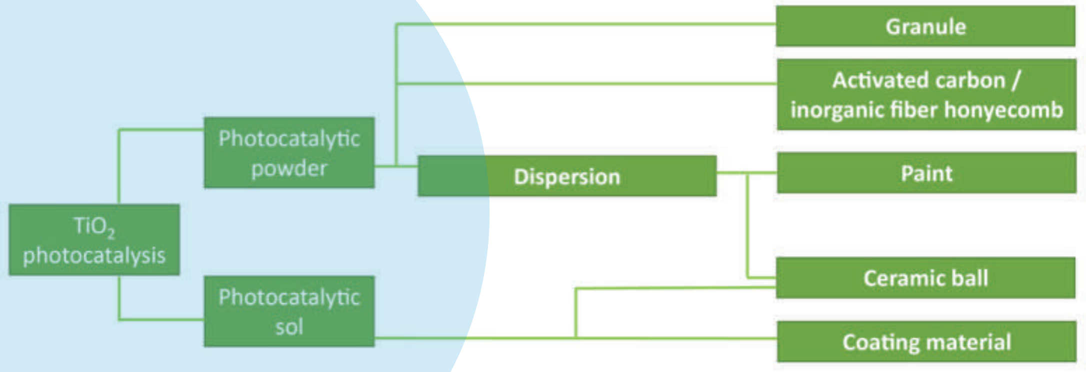


Figure 30. *Variety of TiO_2 photocatalysis products in practical use.*

Photocatalytic coatings can be applied for numerous well different environmental purposes, namely:

- sterilisation/anti-microbial;
- deodorisation;
- air pollution improvement;
- self-cleaning;
- water purification.

In the iSCAPE project, only the effects on air pollution were considered and analysed, and therefore the following recommendations only apply to this particular use.

6.3.1 General design recommendations

The recommendations given in Table 12 are relevant to general photocatalytic coatings recommendations for their implementation in real-world street canyons for air quality improvement.

Coating applicability	The chosen photocatalytic product must be applicable to concrete structures (e.g. walls and roads) in the city. Because of the surface nature of the photo-oxidation reactions of NO, it is necessary that the TiO_2 is present on the surface of the walls/road to be efficient on air pollutants.
Durability	In general, products greatly differ upon their durability with time which can be assessed with the mechanical resistance and freeze-thaw experiments.

Adherence	Available products differ as for the adhesion of TiO_2 coating on concrete tiles.
Performance	The available products differ regarding the pollutant degraded and the performance in air pollution reduction, with differences concerning the NO_x and VOC reduction.
Photoactivity and response to visible/UV-light	Not all commercially available products are equally photoactive/responsive to visible/UV light.
Deposition method	Different deposition methods with different advantages and disadvantages are available: spraying, screen printing, ink-jet printing, roller printing, dip coating, liquid-phase coating.

Table 12. *General recommendations on photocatalytic coatings selection for implementation in a real-world street canyon for air pollution improvement.*

Further recommendations apply regarding the impact of meteorological conditions on the site under interest (Table 13).

Solar radiation	The strongest reductions are observed to the maximum UV sunlight, around noon. Sites often affected by cloudy conditions are not appropriate for interventions with photocatalytic coatings
Wind direction	The largest reductions are observed with wind perpendicular to the painted wall
Seasonal effects	Although summer is the season with the longest sunshine duration and therefore greater availability of UV sunlight for activation of photocatalysis, the presence of some shadows on parts of the walls of the canyon at noon may enhance the reduction; reductions may be larger in winter sunny days, around noon

Table 13. *General recommendations concerning the impact of meteorological conditions for the application of photocatalytic coatings in real-world street-canyons (source: deliverables 3.6 and 3.8).*

Due to the dependence of the reduction on the distance from the coated walls, with the greatest reductions observed in the first 25-50 cm of the activated surface and up to 3-5 m distance, when coming to their application in real-world street canyons it is recommended to treat both the walls and the asphalt to reach the greatest reductions.

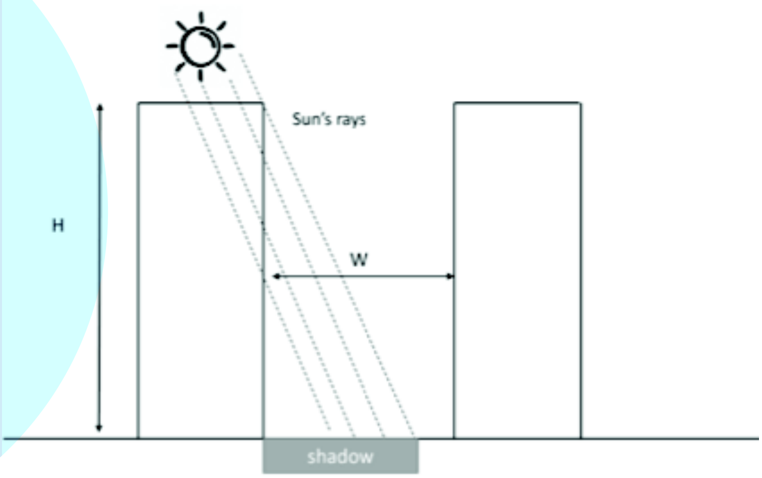
Recalling the previous sketch of street canyons (Figure 27), and considering their classification according to the aspect ratio H/W:

H/W ≥ 2 = deep or narrow street canyons

0.5 < H/W < 2 = moderately deep street canyons

H/W ≤ 0.5 = shallow or wide street canyons

As previously outlined, deep street canyons are those which can experience the worst air quality due to the limited air exchange between the air inside the canyon and the fresh air above. However, when analysing the potential of photocatalytic coatings in improving air quality, the problem with deep street canyons involves the reduced solar exposure due to the greater shadowing effect during daytime in deep street canyons compared with shallow street canyons. In general shallow canyons allow solar exposure to most part of the wall and ground surfaces leading to a higher amount of energy transfer between the canyon surfaces and overlying air, thereby allowing the greatest potential of pollution reduction through photocatalytic coatings. Conversely, in deeper canyons taller bounding buildings impede solar access, increase average coverage of shadow-cast, reduce surface and radiant energy, thereby limiting the potential of activation of photocatalytic coatings. Therefore, photocatalytic coatings present their greatest potential of application in shallow street canyons. These general recommendations are summarised and depicted in Table 14.

Street canyon aspect ratio	**Sketch** (wind direction roughly perpendicular to the street)
H/W ≥ 2 (deep or narrow street canyons) Recommended: ○ Photocatalytic coatings - No, limited activation	

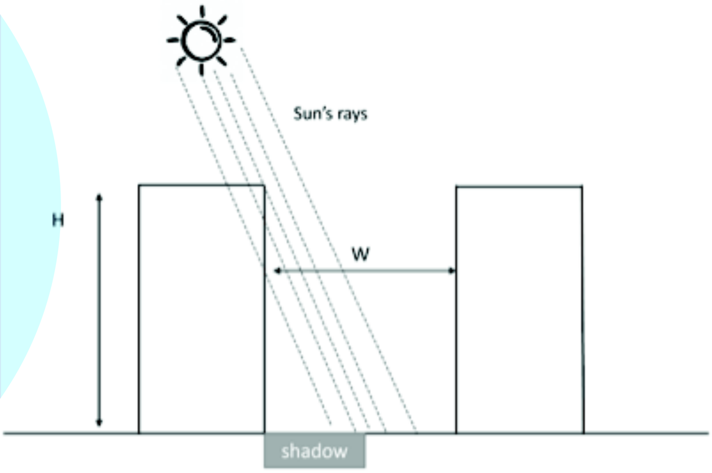
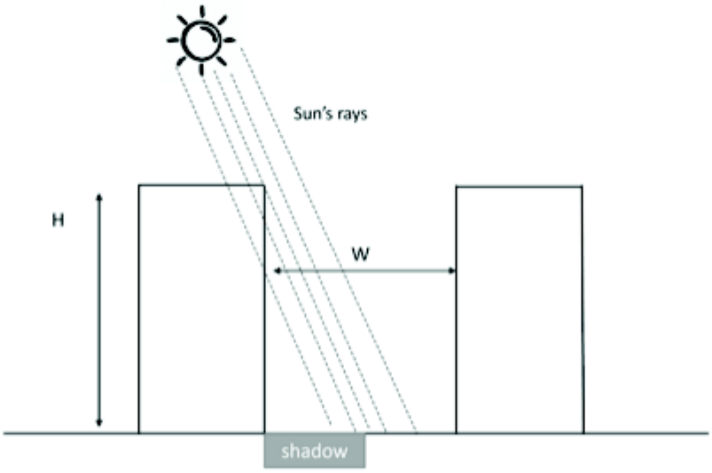
Street canyon aspect ratio	**Sketch** (wind direction roughly perpendicular to the street)
0.5 < H/W < 2 (moderately deep (nearly regular; i.e. w~=h) street canyons) Recommended: ○ Photocatalytic coatings - Yes	
H/W ≤ 0.5 ((shallow or wide street canyons) Recommended: ○ Photocatalytic coatings - Yes, greatest activation	

Table 14. *General recommendations for application of photocatalytic coatings in real-world street canyons with different aspect ratios (edited from deliverables 3.6 and 3.8).*

6.4 Urban development and planning considerations

Urban design and planning as well as their decision-making processes are essential means of controlling and reducing environmental and climatic impacts. Many studies on the causes and effects of air pollution and UHI have shown that the design of spatial and urban structures can play an important role in limiting energy consumption and climate-relevant emissions in mitigating air pollution and UHI (e.g. Levermore et al. 2018; Makar et al. 2006; Rajagopalan et al. 2014; Rizwan et al. 2008). Since the urban climate and emission level (concentration and distribution) are directly related to the design of the (built) environment, changes in the urban structure can modify the local climate and air quality both positively and negatively.

Strategies to mitigate and reduce air pollution and UHI are interlinked in the complex and dynamic contexts and impact chains of urban systems. Urban development and design face the challenge of finding tailor-made solutions. A concrete municipal strategy process is highly dependent on specific initial situations and framework conditions of cities: because of long planning processes and periods, the persistence of built infrastructures and complex urban systems, local authorities need to act early to the causes and effects of air pollution and UHI (also in the context of climate change) and need to take these into account in the planning process.

The selection, evaluation and prioritisation of measures for climate adaptation and air pollution control are generally context-dependent and have to involve political decision-makers, experts and stakeholders in order to take into account the different perspectives, interests and objectives. This ensures that, on the one hand, existing expertise on the framework conditions and interrelationships of measures is taken into account, and, on the other hand, that demands, information needs and preferences can be incorporated into the selection of measures. This can increase political acceptance and relevance as well as the integration and implementation of adaptation measures.

There is no ideal-typical planning process for municipalities, but fundamental stages can be distinguished. These stages are based on the policy cycle (see Figure 31). This cycle describes a clear and systematic process and can serve as an orientation for the complex and demanding task of developing, implementing and evaluating mitigation and adaptation strategies. To this end, the problem situation of air pollution and UHI must first be understood, and impacts and affected areas identified and assessed, in order to obtain sufficient baseline data. Subsequently, appropriate interventions (e.g. PCSs) can be developed and implemented. In addition, the implementation of interventions should be monitored and their effectiveness assessed so that further action can be adjusted if necessary. All in all, the process is divided into five stages which build on each other. Ideally, all stages are run in sequence. However, the policy cycle also allows to enter a freely selected stage of the process according to the initial situation of the municipality and the framework conditions.

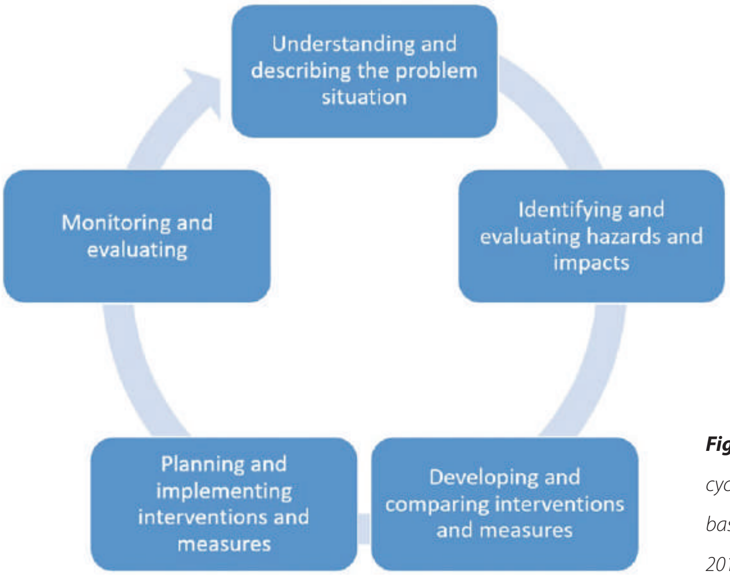


Figure 31. *Policy cycle (own figure based on BBSR 2016, p. 13).*

The iSCAPE project has already elaborated a number of basics for various European cities and has shown how to deal with UHI and air pollution at different stages of the policy cycle. These include various research approaches and methods, such as general analyses of the urban areas and settlements structures, SWOT analyses, stakeholder analyses, climate simulations (local, regional), socio-economic assessments, and monitoring with sensor technologies. The related investigations and associated documents provide various clues and insights into how to proceed and develop content for the policy cycle for mitigation and adaptation.

Building on the policy cycle, the coordination of interventions such as PCSs is recommended within an integrated action plan (see section 5.5), an informal urban development policy instrument that addresses the different stages of the policy cycle. It is a strategic instrument which is not bound by planning law and can be tailored to the needs and demands of an affected city. The iSCAPE action plan (see deliverable 3.9 Report on potentialities of urban interventions and actions) also provides further guidance on the selection of tailor-made and cost-effective interventions.

An action plan is developed in a participatory manner and by involving various experts and non-state stakeholders (Tang et al. 2010). This supports the integrated and interdisciplinary approach required by the challenges of air pollution and UHI in the complex urban system. At the same time, the participation of different groups of people (administration, politics, economy, population) increases the acceptance of strategies and measures. Environmental and climate recommendations should pay close attention on the imperative role, capacities and motivations of urban governance and management organisations (Parsaee et al. 2019). In addition, mitigation and adaptation strategies need to consider public needs and willingness. An action plan with its participatory nature can serve as a collaborative approach to cope with the challenges of air pollution and UHI.

7. Conclusion

This deliverable has summarised the key findings from research and reviews undertaken as part of the iSCAPE project by each of the LL partner cities. Guildford (England, UK), Bologna (Italy), Dublin (Ireland), and Vantaa (Finland) have investigated impacts of specific PCSs on air quality, while Bottrop (Germany) and Hasselt (Belgium) have investigated the impacts of urban infrastructural design and behavioural changes, both under the current climate scenario and from a future climate change perspective. Key findings from these studies have been separated into those that pertain to air quality improvement (section 3), climate change mitigation and adaptation (section 4), and interactions between climate change and ambient air quality (section 5). Finally, the findings have been used to generate a series of general recommendations (section 6) regarding infrastructural interventions, including PCSs, for improved air quality and climate change mitigation and adaptation. The viability of each individual intervention has been summarised, with any positive or negative effects highlighted.

The contents of this report have been reviewed by an advisory board of experts, associated partners, and stakeholders from different cities, and their feedback and answers to a list of co-created questions (see Appendix) have been addressed in this final draft. This collaborative and iterative process has culminated in a vigorous report that may be used by policy-/decision-makers for the effective implementation of infrastructural interventions to improve public health, reduce the costs associated with poor health, and support urban sustainability under a changing global climate.

8. Acknowledgements

The views expressed in this deliverable are the sole responsibility of the authors and do not necessarily reflect the position of the EU. The guidance provided herein is intended to describe best practice subject to the scientific evidence available at the time of writing. Many uncertainties remain, and revised guidance will be issued as these are addressed through further research. The authors also gratefully acknowledge the support of Guildford Borough Council, Municipality of Bologna, Dublin City Council, Municipality of Bottrop, and City of Vantaa from the respective cities of Guildford (UK), Bologna (Italy), Dublin (Ireland), Bottrop (Germany), and Vantaa (Finland) for their help and providing feedback on this deliverable. The authors are also grateful to a number of contributors from the D7.2 contributing organisations as well as reviewers who supported the production of this deliverable.

9. References / Bibliography

(The references marked with * are outputs from the iSCAPE project that allowed informing the recommendation text of this deliverable)

*Abhijith, K.V. and Kumar, P., 2019. Field investigations for evaluating green infrastructure effects on air quality in open-road conditions. Atmospheric environment, 201, 132-147.

*Abhijith, K.V., Kumar, P., Gallagher, J., McNabola, A., Baldauf, R., Pilla, F., Broderick, B., Di Sabatino, S. and Pulvirenti, B., 2017. Air pollution abatement performances of green infrastructure in open-road and built-up street canyon environments–A review. Atmospheric Environment, 162, 71-86.

Alexandri, E. and Jones, P., 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Building and environment, 43(4), 480-493.

Barry, S., and Cereceda, R., 2019. Why was there a spike in pollution during the European heatwave? euronews, available online at https://www.euronews.com/2019/07/04/why-was-there-a-spike-in-pollution-during-the-european-heatwave.

*Barwise, Y. and Kumar, P., 2019. Designing vegetation barriers for urban air pollution abatement: a practical review for appropriate species selection. Under review.

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

Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR), 2016. Anpassung an den Klimawandel in Stadt und Region: Forschungserkenntnisse und Werkzeuge zur Unterstützung von Kommunen und Regionen. 2016th ed. Bonn: Bundesinstitut für Bau-Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR).

Chazan, D. 2019. France braces for second heatwave amid fears of pollution spike. The Telegraph, available online at https://www.telegraph.co.uk/news/2019/07/21/france-braces-second-heatwave-amid-fears-pollution-spike/.

Chen, X., Pei, T., Zhou, Z., Teng, M., He, L., Luo, M. and Liu, X., 2015. Efficiency differences of roadside greenbelts with three configurations in removing coarse particles (PM_{10}): A street scale investigation in Wuhan, China. Urban Forestry & Urban Greening, 14(2), 354-360.

Coumou, D., Lehmann, J., Beckmann, J., 2015. The weakening summer circulation in the Northern Hemisphere mid-latitudes. Science, 348(6232), 324-327.

DEFRA, 2018. Air Quality Expert Group, Impacts of Vegetation on Urban Air Pollution. https://uk-air.defra.gov.uk/ (accessed on June 2019).

EEA (European Environment Agency), 2016a. Climate change, impacts and vulnerability in Europe 2016. An indicator-based report. EEA Report No 1/2017. Copenhagen: EEA.

EEA (European Environment Agency), 2016b. Urban adaptation to climate change in Europe 2016. Transforming cities in a changing climate. EEA Report No 12/2016. Copenhagen: EEA.

Ferranti, E., MacKenzie, A., Levine, J., Ashworth, K., Hewitt, C., 2019. First Steps in Urban Air Quality. Second Edition. A Trees and Design Action Group (TDAG) Guidance Document. http://epapers.bham.ac.uk/3069/1/Ferranti_etal_2019_FirstStepsAQ.pdf (accessed on June 2019).

Filleul, L., Cassadou, S., Médina, S., Fabres, P., Lefranc, A., Eilstein, D., Le Tertre, A., Pascal, L., Chardon, B., Blanchard, M., Declercq, C., Jusot, J.F., Prouvost, H., Ledrans, M., 2006. The relation between temperature, ozone, and mortality in nine French cities during the heat wave of 2003. Environ Health Perspect, 114(9), 1344-1347.

Fiore, A.M., Naik, V., Spracklen, D.V., Steiner, A., Unger, N., Prather, M., Bergmann, D., Cameron-Smith, P.J., Cionni, I., Collins, W.J., Dalsøren, S., Eyring, V., Folberth, G.A., Ginoux, P., Horowitz, L.W., Josse, B., Lamarque, J.-F., MacKenzie, I.A., Nagashima, T., O'Connor, F.M., Righi, M., Rumbold, S.T., Shindell, D.T., Skeie, R.B., Sudo, K., Szopa, S., Takemura, T., Zeng, G., 2012. Global air quality and climate. Chem Soc Rev, 41, 6663-6683.

Fiore, A.M., Naik, V., and Leibensperger, E.M., 2015. Air quality and climate change connections. Journal of the Air & Waste Management Association, 65(6), 645-685.

Forzieri, G., Feyen, L., Russo, S., Vousdoukas, M., Alfieri, L., Outten, S., Migliavacca, M., Bianchi, A., Rojas, R. and Cid, A., 2016. Multi-hazard assessment in Europe under climate change. Climatic Change, 137(1-2), 105-119.

Gallagher, J. (2013a). An Investigation of the Passive Control of Air Pollution in the Urban Environment (Doctoral dissertation, Trinity College Dublin).

Gallagher, J., Gill, L.W. & McNabola, A. (2013b). The passive control of air pollution exposure in Dublin, Ireland: A combined measurement and modelling case study. Science of the Total Environment, 458, 331-343.

Garrido-Perez, J.M., Ordóñez, C., García-Herrera, R., Barriopedro, D., 2018. Air stagnation in Europe: spatiotemporal variability and impact on air quality. Science of the Total Environment, 645, 1238-1252.

*Greater London Authority, 2019. Using Green Infrastructure to Protect People from Air Pollution. https://www.london.gov.uk/WHAT-WE-DO/environment/environment-publications/using-green-infrastructure-protect-people-air-pollution (accessed on August 2019).

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Schoch, D., Siikamäki, J.V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S.M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F.E., Sanderman, J., Silvius, M., Wollenberg, E., and Fargione, J., 2017. Natural climate solutions. PNAS, 114(44),11645-11650.

Gromke, C., Jamarkattel, N. and Ruck, B., 2016. Influence of roadside hedgerows on air quality in urban street canyons. Atmospheric environment, 139, 75-86.

Heal, M.R., Kumar, P., and Harrison, R.M., 2012. Particles, air quality, policy, health. Chemical Society Reviews, 41, 6606-6630.

Hong, C., Zhang, Q., Zhang, Y., Davis, D.J., Tong, D., Zheng, Y., Liu, Z., Guan, D., He, K., Schellnhuber, H.J., 2019. PNAS, 116(35), 17193-17200.

Horton, D.E., Harshvardhan, and Diffenbaugh, N.S., 2012. Response of air stagnation frequency to anthropogenically enhanced radiative forcing. Environmental Research Letters, 7(4):044034.

IPCC, 2013. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC, 2018. Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp.

Jacob, D.J., and Winner, D.A., 2009. Effect of climate change on air quality. Atmospheric Environment, 43(1), 51-63.

*Kalaiarasan, G., Kumar, P., Tiwari, A., and Ottosen, T.-B., 2020. The impacts of existing and hypothetical green infrastructures on urban heat island formation. In preparation.

Kew, S.F., Philip, S.Y., van Oldenborgh, G.J., Otto, F.E.L., Vautard, R., van der Schier, G., 2019. The exceptional summer heat wave in southern Europe 2017. In: Explaining extremes of 2017 in a climate perspective. BAMS, 100(1), S49-S53.

Kinney, P.L., 2008. Climate change, air quality, and human health. American Journal of Preventive Medicine, 35(5), 459-467.

*Kumar, P., Druckman, A., Gallagher, J., Gatersleben, B., Allison, S., Eisenman, T.S., Hoang, U., Hama, S., Tiwari, A., Sharma, A., Abhijith, K.V., Adlakha, D., McNabola, A., Astell-Burt, T., Feng, X., Skeldon, A.C., de Lusignan, S., and Morawska, L., 2019a. The nexus between air pollution, green infrastructure and human health. Environmental International, 133, 105181.

*Kumar, P., Abhijith, K.V. and Barwise, Y., 2019b. Implementing Green Infrastructure for Air Pollution Abatement: General Recommendations for Management and Plant Species Selection. DOI: 10.6084/m9.figshare.8198261.v1.

Levermore, G., Parkinson, J., Lee, K., Laycock, P. and Lindley, S., 2018. The increasing trend of the urban heat island intensity. Urban climate, 24, 360-368.

Li, X.B., Lu, Q.C., Lu, S.J., He, H.D., Peng, Z.R., Gao, Y. and Wang, Z.Y., 2016. The impacts of roadside vegetation barriers on the dispersion of gaseous traffic pollution in urban street canyons. Urban forestry & urban greening, 17, 80-91.

Likhvar, V.N., Pascal, M., Markakis, M., Colette, A., Hauglustaine, D., Valari, M., Klimont, Z., Medina, S., and Kinney, P., 2015. A multi-scale health-impact assessment of air pollution over the 21st century. Science of the Total Environment, 514, 439-449.

Loughner, C.P., Allen, D.J., Zhang, D.L., Pickering, D.E., Diskerson, R.R., and Landry, L., 2012. Roles of urban tree canopy and buildings in urban heat island effects: parameterization and preliminary results. Journal of Applied Meteorology and Climatology, 51, 1775-1793.

Madaniyazi, L., Guo, Y., Yu, W., and Tong, S., 2015. Projecting future air pollution-related mortality under a changing climate: progress, uncertainties, and research needs. Environment International, 75, 21-32.

Makar, P.A., Gravel, S., Chirkov, V., Strawbridge, K.B., Froude, F., Arnold, J. and Brook, J., 2006.

Heat flux, urban properties, and regional weather. Atmospheric Environment, 40(15), 2750-2766.

Matthews, T., Lo, A.Y., and Byrne, J.A., 2015. Reconceptualizing green infrastructure for climate change adaptation: barriers to adoption and drivers for uptake by spatial planners. Landscape and Urban Planning, 138, 155-163.

Mitchell, D., Heaviside, C., Vardoulakis, S., Huntingford, C., Masato, G., Guillod, B.P., Frumhoff, P., Bowery, A., Wallom, D., Allen, M., 2016. Attributing human mortality during extreme heat waves to anthropogenic climate change. Environmental Research Letters, 11, 074006.

OECD (Organization for Economic Cooperation and Development) 2014. The Cost of Air Pollution. Health Impacts of Road Transport. Paris: OECD Publishing.

Ogren, T.L., 2015. The allergy-fighting garden: stop asthma and allergies with smart landscaping. Ten Speed Press.

Ordóñez, C., H. Mathis, M. Furger, S. Henne, C. Hüglin, J. Staehelin, and A. S. H. Prévôt. 2005. Changes of daily surface ozone maxima in Switzerland in all seasons from 1992 to 2002 and discussion of summer 2003. Atmos. Chem. Phys. 5(5): 1187–203.

*Ottosen, T.-B. and Kumar, P., 2020. The influence of the vegetation cycle on the mitigation of air pollution by a deciduous roadside hedge. Sustainable Cities and Society, 53, p.101919.

WHO (World Health Organization) 2016. Health risk assessment of air pollution – general principles. Copenhagen: WHO Regional Office for Europe.

Parsaee, M. Joybari, M.M., Mirzaei, P.A., Haghighat, F., 2019. Urban heat island, urban climate maps and urban development policies and action plans, Environmental Technology & Innovation, 14, 100341.

Pellegrini, E., Lorenzini, G., and Nali, C., 2007. The 2003 European Heat Wave: Which role for ozone? Some data from Tuscany, Central Italy. Water, Air, and Soil Pollution, 181(1-4), 401-408.

Perini, K. and Magliocco, A., 2014. Effects of vegetation, urban density, building height, and atmospheric conditions on local temperatures and thermal comfort. Urban Forestry & Urban Greening, 13(3), 495-506.

Putaud, J.-P., Raes, F., van Dingenen, R., Brüggermann, E., Facchini, M.C., Decesari, S., Fuzzi, S., Gehrig, R., Hüglin, C., Laj, P., Lorbeer, G., Maenhaut, W., Mihalopoulos, N., Müller, K., Querol, X., Rodriguez, S., Schneider, J., Spindler, G., ten Brink, H., Tørseth, K., Wiedensohler, A., 2004. A European aerosol phenomenology - 2: chemical characteristics of particulate matter at kerbside, urban, rural, and background sites in Europe. Atmospheric Environment, 38(6), 2579-2595.

Rajagopalan, P., Lim, K.C. and Jamei, E., 2014. Urban heat island and wind flow characteristics of a tropical city. Solar Energy, 107, 159-170.

Razzaghmanesh, M., Beecham, S. and Salemi, T., 2016. The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. Urban Forestry & Urban Greening, 15, 89-102.

Rizwan, A.M., Dennis, L.Y. and Liu, C. 2008. A review on the generation, determination and mitigation of Urban Heat Island. Journal of Environmental Sciences, 20(1), 120–128.

Santamouris, M., Mihalakakou, G., Papanikolaou, N. and Asimakopoulos, D.N., 1999. A neural network approach for modeling the heat island phenomenon in urban areas during the summer period. Geophysical Research Letters, 26(3), 337-340.

Seto K. C., S. Dhakal, A. Bigio, H. Blanco, G. C. Delgado, D. Dewar, L. Huang, A. Inaba, A. Kansal, S. Lwasa, J. E. McMahon, D. B. Müller, J. Murakami, H. Nagendra, and A. Ramaswami, 2014. Human Settlements, Infrastructure and Spatial Planning. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Shashua-Bar, L., Pealmutter,D., and Erell, E., 2010. The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. International Journal of Climatology, 31, 1498-1506.

Silva, R.A., West, J.J., Lamarque, J.-F., Shindell, D.T., Collins, W.J., Dalsoren, S., Faluvegi, G., Folberth, G., Horowitz, L.H., Nagashima, T., Naik, V., Rumbold, S.T., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Cionni, I., Doherty, R. M., Eyring, V., Josse, B., MacKenzie, I.A., Plummer, D., Righi, M., Stevenson, D.S., Strode, S., Szopa, S., and Zeng, G., 2016. The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. Atmospheric Chemistry and Physics, 16, 9847-9862.

Solberg, S., Hov, Ø., Søvde, A., Isaksen, I.S.A., Coddeville, P., De Backer, H., Forster, C., Orsolini, Y., and Uhse, K., 2007. European surface ozone in the extreme summer 2003. Journal of Geophysical Research, 113, D07307.

Stowell, J.D., Kim, Y.M., Gao, Y., Fu, J.S., Chang, H.H., and Liu, Y., 2017. The impact of climate change and emissions control on future ozone levels: implications for human health. Environment International, 108, 41-50.

Susca, T., Gaffin, S.R. and Dell'Osso, G.R., 2011. Positive effects of vegetation: Urban heat island and green roofs. Environmental pollution, 159(8-9), 2119-2126.

Tainio, M., Juda-Rezler, K., Reizer, M., Warchalowski, A., Trapp, W., Skotak, K., 2013. Future climate and adverse health effects caused by fine particulate matter air pollution: case study for Poland. Regional Environmental Change, 13(3), 705-715.

Tang, Z., Brody, S.D., Quinn, C., Chang, L., Wei, T., 2010. Moving from agenda to action: evaluating local climate change action plans. Journal of Environmental Planning and

Management, 53(1), 41–62.

*Tiwari, A., Kumar, P., Baldauf, R., Zhang, K.M., Pilla, F., Di Sabatino, S., Brattich, E. and Pulvirenti, B., 2019a. Considerations for evaluating green infrastructure impacts in microscale and macroscale air pollution dispersion models. Science of the Total Environment, 672, 410-426.

*Tiwari, A., Kumar, P., 2019b. Integrated dispersion-deposition modelling for air pollutant reduction via green infrastructure at an urban scale. In Preparation.

Tressol, M., C. Ordonez, R. Zbinden, et al. 2008. Air pollution during the 2003 European heat wave as seen by MOZAIC airliners. Atmos. Chem. Phys. 8(8): 2133–50. Walsh, C.L., et al., 2011. Assessment of climate change mitigation and adaptation in cities. Proceedings of the Institution of Civil Engineers - Urban Design and Planning, 164 (2), 75–84.

Vautard, R., Colette, A., van Meijgaard, E., Meleux, F., van Oldenborgh, G.J., Otto, F., Tobin, I., and Yiou, P., 2018. Attribution of wintertime anticyclonic stagnation contributing to air pollution in western Europe. BAMS, doi:10.1175/BAMS-D-17-0113.2.

Vautard, R., van Oldenborgh, G.J., Otto, F., Vogel, M.M., Seneviratne, S.I., Soubeyroux, J.-M., Schneider, M., Drouin, A., Ribes, A., Kreienkamp, F., Stott, P., van Aalst, M., 2019. Human contribution to the record-breaking July 2019 heat wave in western Europe. Available online at: https://www.worldweatherattribution.org/wp-content/uploads/July2019heatwave.pdf.

Vieno, M., A. J. Dore, D. S. Stevenson, R. Doherty, M. R. Heal, S. Reis, S. Hallsworth, L. Tarrason, P. Wind, D. Fowler, D. Simpson and M. A. Sutton. 2010. Modelling surface ozone during the 2003 heat-wave in the UK. Atmos. Chem. Phys. 10(16): 7963–78. doi:10.5194/acp-10-7963-2010.

Vogel, M.M., Zscheischler, J., Wartenburger, R., Dee, D., Seneviratne, S.I., 2019. Concurrent 2018 hot extremes across northern Hemisphere due to human-induced climate change. Earth's future, 7(7), 692-703.

Vos, P.E., Maiheu, B., Vankerkom, J. and Janssen, S., 2013. Improving local air quality in cities: to tree or not to tree?. Environmental pollution, 183, 113-122.

Votsis, A, 2017. Space and Price in Adapting Cities : Exploring the Spatial Economic Role of Climate-Sensitive Ecological Risks and Amenities in Finnish Housing Markets. PhD Dissertation, Univ. of Helsinki, 21 p. http://urn.fi/URN:ISBN:978-952-336-009-9.

Walsh, C.L., Dawson, R.J., Hall, J.W., Barr, S.L., Batty, M., Bristow, A.L., Carney, S., Dagoumas, A.S., Ford, A.C., Harpham, C., Tight, M.R., Watters, H., Zanni, A.M., 2011. Assessment of climate change mitigation and adaptation in cities. Proceedings of the Institution of Civil Engineers - Urban Design and Planning, 164(2), 75–84.

Wania, A., Bruse, M., Blond, N. and Weber, C., 2012. Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations. Journal of environmental management, 94(1), 91-101.

Weaver, C. P., E. Cooter, R. Gilliam, et al. 2009. A preliminary synthesis of modeled climate change impacts on U.S. regional ozone concentrations. Bull. Am. Meteorol. Soc. 90(12): 1843–63.

Williamson, K., Satre-Meloy, A., Velasco, K., and Green, K., 2018. Climate change needs behaviour change: making the case for behavioural solutions to reduce global warming. Arlington, VA: Rare. Available online at: https://rare.org/wp-content/uploads/2019/02/2018-CCNBC-Report.pdf.

Appendix

The table below summarises the key feedback provided by stakeholders from different organisations.

Stakeholder organisation name	Type of interventions	Summary of feedback
Guildford Borough Council, Guildford, UK	**Hedges and trees in urban, open road environments**	● The report may be used to promote the use of GI in urban areas. ● The report will have an impact on the development of PCSs and GI in the Guildford area. It supports Guildford Borough Council's aim to increase GI cover (particularly trees and hedges) for the benefit of the environment generally, and will provide direction and assistance as options are considered. The report is also useful while considering options for targeted measures to improve air quality at specific locations. ● Regarding GI implementation in the Guildford area, several management issues have arisen (some of which were already mentioned in the report), including: ○ The impact of potential GI on existing roadside utilities (e.g. water, gas, electricity) and infrastructure must be considered and may be a barrier to implementation. ○ The soil and current land use type must be considered ○ Pedestrian safety, in terms of lighting and visibility, must be considered. ● In order to transform this report into GI planting guidance that complies with relevant regulations, dialogue between researchers and planning policy teams at local authority level is required. ● Guidance for practitioners to efficiently assess the suitability of potential GI schemes would be a useful next step.

Municipality of Bologna, Bologna, Italy	**Green infrastructural interventions in street canyons, climate change mitigations, interlinkages between air quality and climate change, and photocatalytic coating**	● The report plays a significant role to improve air quality strategies, increase know-how about this topic and offer a precious tool in support of urban forestation policies. ● The report supports the work of the Municipality in building rules and support project-evaluation. The deliverable analyses several passive systems to save energy and improve air quality. ● The suggestion to include other passive systems like roof pound, underground house, wind catcher, was not considered since these passive systems were beyond the scope of the iSCAPE project and were not analysed by any of the project partners. ● The suggestion to define specific categories of intervention such as green roofs, green walls, buildings facade, gardens, porches, boulevard supported by explanatory examples about possible planning solutions for each geographical area and/or situation (building orientation, altitude, solar radiation effect, rainfall, temperature, wind, etc.) was not considered as the report should remain general. ● The suggestion to produce explanatory leaflets of possible intervention with details of benefits, costs, water requirement and maintenance in a similar way to the project "Rigenerare la città con la natura - Strumenti per la progettazione degli spazi pubblici tra mitigazione e adattamento ai cambiamenti climatici" produced by the Emilia Romagna region, as a way for the user to choose the most suitable solution according to his own context, was taken into consideration and used as a suggestion for the exploitation and dissemination of the findings of the iSCAPE project.
City of Vantaa, Finland	**Urban planning (city Master Plan), green spaces**	● The suggestion to generalise the main recommendations as a graph/infographics, or then clearly and shortly into the executive summary, which would help the stakeholders to understand more easily the main points. ● The suggestion to clearly highlight the uncertainties, limitations etc. of the different methods. ● The suggestion to make clear practical guidelines or templates for the cities for examining the benefit (in health, comfort, costs) of the methods and solutions.

Municipality of Bottrop, Bottrop, Germany	**Urban planning and design, action plans**	● The suggestion to use more layman language and to focus on essential key findings in order to increase practicability (refers to the entire report) ● The suggestion to focus more on political support and influence/interest and to point out short to medium term achievements in order to refer to legislative periods ● The suggestion to point out the city's advantages when implementing the interventions (refers to all interventions described in this report)
Dublin City Council, Dublin, Ireland	**Low-boundary walls**	● To focus on health impacts. ● To focus on interlinks between air pollution and climate change to avoid problem shifting, e.g. solving a specific problem but generating another one. For example, you can tax more vehicles producing GHG to alleviate climate change, but then you might have more people using diesel with high impact on air quality. ● The municipality is very interested in the interlinks between air quality and climate change. It would be interesting to receive some kind of brief from our work outlining the findings. This could be integrated in the future climate action plan for the Greater Dublin Region. ● Continuation of the project in order to establish and consolidate the scientific work of iSCAPE, exchange and cooperation of policy/city administration of the six LL. ● Inclusion of GI as an air pollution control and mitigation solution into the future climate action plan for the Greater Dublin Region. This would be possible only if the project results are presented as evidence based and in an understandable way. The inclusion in the future climate action plan would allow to access local funds to replicate the GI studies and pilots in the city. ● Establishment of "town twinning", mutual learning and implementation of PCS, pioneering role at the European level. ● The municipality showed a great interest in simulations to target both air quality and climate change. This is because sometimes climate change policies are carbon driven, so a policy focused on climate change could neglect air quality and basically shift the problem. ● Create short report on key facts and measures (max. 10-15 pages), translated into simple language and focus on to achieve public and political acceptance.

Notes

iSCAPE

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