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A New Adaptation Strategy to Changing Local Climatic Conditions in Urban Areas? The Use of Leaf-Turning Tree Species

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1 ABSTRACT

The effects of climate change are especially felt in urban areas. Rising temperatures and changing precipitation patterns are challenging the maintenance of green oases in cities. However, urban trees are becoming increasingly important in mitigating these negative climatic effects, as they offer positive cooling potential to the surrounding area through the shading and evaporation capacity of the vegetation. At the same time, they are also susceptible to these weather extremes such as summer heat and drought, resulting in high surface runoff and low infiltration rates. This leads to the problem that native urban tree species, such as large-leaved lime (Tilia platyphyllos) and sycamore maple (Acer pseudoplatanus), are reaching the limits of their adaptability. In contrast, tree species native to south-eastern Europe are better equipped to cope with changing climatic conditions through various adaptations, such as leaf orientation in response to high levels of solar radiation. One potential adaptation strategy is the use of alternate-leaf tree species, which could mitigate the adverse effects of climate change in urban areas and improve the quality of life for residents. In particular, the silver lime (Tilia tomentosa) is becoming increasingly important in this context. It can turn the silvery underside of its leaves upwards when exposed to strong sunlight, leading to a change in the albedo and a possible reduction in surface temperatures in the crown area.

Keywords: city planning, adaption strategies, urban green, climate adaption, urban climate

2 INTRODUCTION

Urban areas have distinct climatic characteristics compared to undeveloped regions. Urban centres experience increased heating during hot periods and reduced cooling at night, which can adversely affect both plants and humans [Roloff 2013, pp. 168]. Many of the emerging risks of climate change are concentrated in urban areas [Kumar 2021, p. 1]. Central European cities are especially affected by the displacement of vegetation, increased storage of sensible heat fluxes, and additional anthropogenic heat emissions [Zhang et al. 2020, p. 1]. At the same time, the majority of the world's population lives in metropolitan areas. In 2022, 78 % of Germany´s population was urban, equivalent to approximately 69 million people [World Bank 2023]. Climate change is predicted to increase risks to people, assets, businesses, and ecosystems in cities. These risks include, for example, increased hazards from heat stress, air pollution storms, and heavy rainfall [Dodman et al. 2022, pp. 909]. The majority of direct weather-related deaths worldwide were attributed to storms (39 %), droughts (34 %), and floods (16 %) [Keim 2020, p. 268]. It is important to note that these risks will be exacerbated for those who lack access to essential infrastructure and services, or who live in high-risk areas [Dodman et al. 2022, pp. 909].

It is highly likely that global warming will exceed 1.5 °C to 2 °C in the 21st century unless significant reductions in carbon dioxide and other emissions are implemented in the next decades [Ara Begum et al. 2022, p. 129]. These rising temperatures can cause health problems such as heat stroke, heat exhaustion, and dehydration. The human body can adapt to heat to some extent, but the risks vary dramatically depending on exposure, location, and susceptibility [Ebi et al. 2021, p. 298]. A 1 °C increase in perceived temperature above city-specific thresholds temperatures is associated with a 3.12 % increase in mortality in Mediterranean cities (such as Athens, Rome, and Milan) and a 1.84 % increase in mortality in Northern European cities (such as Zurich, Stockholm, and Paris) [Baccini et al. 2008, pp. 716]. Extreme heat waves, consisting of several days of hot weather, have a greater impact on mortality than just elevated daily temperatures alone. This is because exceptionally high minimum temperatures prevent recovery from heat stress during the night, resulting in persistent heat stress throughout the day and night [Kenney et al. 2014, p. 1893].

Adaptation to changing local climate conditions is crucial for maintaining the quality of life of urban residents and strengthening the resilience of cities to the impacts of climate change. A resilient city has a high adaptive capacity, which enables it to adjust reactively and proactively to changing environmental conditions and to recover quickly from negative impacts [Birkmann et al. 2013, p. 18; Kuhlicke et al. 2024, p. 271].

There is growing recognition that "nature-based solutions" have the potential to mitigate the impacts of climate change, while also delaying further warming, promoting biodiversity, and securing ecosystem services. However, there are concerns about their reliability and cost-effectiveness when compared to engineered alternatives, as well as their ability to withstand climate change [Seddon et al. 2020, p. 1]. Nature-based solutions involve the use and enhancement of natural ecosystems to address societal problems [Cohen-Shacham et al. 2016, p. 2]. These interventions include a variety of strategies, such as the protection and management of natural and semi-natural ecosystems and the integration of green and blue infrastructure in cities. The concept is based on the premise that both healthy natural and managed ecosystems provide a wide range of services that are critical to human well-being, such as carbon storage, flood management, and clean air. Nature-based solutions range from maintaining or restoring diverse natural ecosystems to developing novel managed or hybrid "grey-green" techniques [Seddon et al. 2020, p. 2]. Hybrid "grey-green" strategies are systems that combine traditional grey infrastructure with nature-based solutions for a variety of applications, including disaster risk reduction and climate change adaptation. Examples of such approaches include rain gardens, green roofs, and street trees planted in pavement tree pits [Depietri & McPhearson 2017, pp. 101]. While urban greenery can provide numerous benefits to the urban climate and human well-being, it is important to acknowledge that prioritising urban greenery varies from person to person. Furthermore, aesthetic preferences are subjective and may change over time. For example, shading or a dark crown may be beneficial on hot summer days, but unfavourable in cool, humid summers [Roloff 2013, p. 29].

Urban trees improve the quality of life by filtering the air, providing moisture, and creating a pleasant urban microclimate. They also play a crucial role in adapting to climate change by protecting against the effects of heat and drought. In addition, they can contribute to biodiversity and perform essential functions for the urban climate and biodiversity by forming complex ecosystems [Roloff 2013, pp. 15-22]. However, the environment in which urban trees grow is very different from their natural habitat, which can affect their performance and lifespan [Breuste 2019, p. 151]. Urban trees often have a life expectancy of only 50 % of their potential age range, while street trees have a life expectancy of only 25 % [Roloff 2013, p. 8]. These aggravating conditions include small tree grates, soil compaction, reduced gas and water exchange, and a lack of rainwater due to sealing and pollutants in the immediate environment (such as road salt and car exhaust). This results in significantly shorter lifespans and lower performance, which are often in high demand [Breuste 2019, p. 151]. In addition, higher air temperatures due to urban heat islands, make trees in urban areas increasingly vulnerable to weather extremes, especially summer heat and drought. Native urban trees, such as the summer lime tree (Tilia platyphyllos) and sycamore maple (Acer pseudoplatanus), have been shown to approach their limits of adaptability. However, continental, non-native species are often characterised by greater stress tolerance, increased vitality, and longer foliage length [Böll et al. 2021, p. 3]. To continue to provide cities with the benefits of urban trees it is therefore essential to select tree species that are better adapted to changing climatic conditions and to protect and preserve these trees as an important adaptation measure to adapt to climate change [Roloff 2013, p. 168].

3 TILIA TOMENTOSA

Tilia tomentosa, also known as the silver lime in the United Kingdom and the silver linden in the United States, is a drought-tolerant and thermophilic tree species native to southeastern Europe. It naturally occurs in the Balkan Peninsula and north-western Turkey as well as in Hungary and Romania [Bartha 1995, p. 5; Heinrichs et al. 2021, p. 1; Kleber et al. 2022, pp. 41]. It has been part of horticultural cultivation since 1767 and has been used as a street tree for many years. It is specifically important for urban and green space planning because it tolerates heat, air, and drought better than native lime species. The silver lime tree was included in the "Urban Green 2021" project in 2009 because of its heat and drought tolerance and has proven to be particularly robust in the hot and dry location of Würzburg. Research conducted as part of the project shows that the silver lime maintains lower leaf temperatures during heat waves than the small-leaved lime (Tilia cordata). This is probably due to its silver-haired leaves (refer to Fig. 1) and the ability to actively turn its leaves in hot weather (refer to Fig. 2). As a result, the silver lime tree is less likely to exceed critical temperature thresholds compared to the small-leaved lime tree [Schönfeld 2022, pp. 2-6]. Therefore, Tilia tomentosa is classified as highly suitable for drought tolerance and suitable for cold hardiness [Roloff 2013, pp. 176-182].

Figure 1: Photograph depicting the leaves of a silver lime tree located in Kaiserslautern, Buchenlochstraße, on 22 August 2023. The photograph shows the contrast between the dark green upper side and the light, silvery underside of the leaves [Geib 2023].

The flowers of the silver lime are grouped in pendulous inflorescences. The main axis of the inflorescence is partially united with a silvery-white, smooth-edged, and elongated subtending leaf. The individual flowers are almost white. It flowers in July and is pollinated by bees and other insects. Its fruits are nuts that grow in an inflorescence with a parchment-like support leaf. They are pointed and egg-shaped, ripen in September and October and are dispersed by the wind [Bachofer & Mayer 2021, p. 100]. It was previously assumed that the silver lime was responsible for the increased bumblebee mortality because its nectar was considered toxic to insects. However, recent research has disproven this theory. The actual cause of the widespread bumblebee mortality under silver lime trees is food competition among the insects [Koch & Stevenson 2017, p. 8; Roloff 2013, p. 159; Jacquemart et al. 2018, para. 3.3.2].

The leaves of the silver lime are initially covered with star-shaped hairs on the upper side but often become completely bare later [Binder 2015, p. 23]. The underside of the leaves has a dense layer of star-shaped hairs, giving them a silvery appearance, and sunken stomata [Böll et al. 2021, p. 5; Binder 2015, p. 23]. This hairy layer prevents aphid infestation and honeydew, while also protecting against heat and excessive evaporation [Roloff 2013, p. 159]. When exposed to extreme heat, the silver lime tree turns its leaves so that the lighter underside faces upwards, reflecting the incoming solar radiation. The change in albedo reduces the surface temperature of the canopy (refer to Fig. 2) as well as the air temperature under the canopy and around the trunk area [Henninger 2020, p. 76].

Figure 2: Thermal imaging camera images before rotation (left), during rotation (centre), and after rotation (right). High surface temperatures are represented by red-coloured areas and lower surface temperatures by blue areas [Henninger 2020, p. 76].

4 METHODS

This research project aims to investigate the use of leaf-turning tree species as a possible adaptation strategy to changing climatic conditions in urban areas. The focus will be on analysing the changing albedo and decreasing surface temperature at the canopy of the silver leaf and its potential impact on the immediate environment, particularly concerning its use as a roadside greenery [Geib & Henninger 2023, p. 43].

4.1 Study area

The measurements are carried out in the city of Kaiserslautern (49° 26‘ 36‘‘ N, 7° 46‘ 08‘‘ E), Rhineland-Palatinate, Germany. Kaiserslautern is a university and industrial city, with an urban area of about 140 km2. In particular, about 62 % of the area is covered by forest, which corresponds to 87 km2 [Geiger 2013, p. 54]. The city's average annual temperature is 10.2 °C, with air temperatures ranging from an average between 1.9 °C in January to 19.3 °C in July [Deutscher Wetterdienst 2023a]. The average annual temperature in Kaiserslautern has increased significantly by 2.0 K since the end of the 19th century, especially in recent decades [Stadtverwaltung Kaiserslautern 2019, p. 6]. Furthermore, Kaiserslautern has an annual precipitation of 764 mm, with the highest amount of 69 mm being recorded in May [Deutscher Wetterdienst 2023b].

4.2 Site and tree selection

The in-situ measurements are carried out at various locations throughout the city, all of which are roadside green spaces. Streets are selected based on tree species, stage of development phase, and the presence of a direct comparison tree (refer to Fig. 3).

According to the GALK list of street trees, there are differences in the suitability of different species of silver lime as street trees. Therefore, Tilia tomentosa ‘Brabant’ (well suited) and Tilia tomentosa (limited suitability) will be investigated to verify possible intraspecific differences [GALK 2024]. In addition, the influence of the development phase is considered in the measurements. As trees use different adaptation strategies depending on their life stage, the silver lime trees are divided into the phases of youth, maturity and old age. This makes it possible to determine the dominant leaf-turning ability within a particular age group [Geib & Henninger 2023, p. 44].

As the measurements are made in the street and not under laboratory conditions, a reference tree (of any species) and a silver lime tree should ideally be placed directly next to each other. This will allow a direct comparison of the values as the trees are in similar environments.

All studied silver lime trees surveyed are measured for their physical characteristics, including height, diameter at breast height, crown base height, and crown radius. The Department of Environmental Protection in Kaiserslautern, Germany, maintains a database containing information on all the silver lime trees in the city, including botanical name, trunk diameter (1.3 m a.g.l.), crown diameter, tree height, estimated age, vitality, stage of development, and traffic significance. This data is used to select and identify silver lime trees.

4.3 Meteorological selection criteria

The aim of this study is to investigate the impact of trees on the microclimate of street canyons during warm summer conditions and extreme heat, as this is when the cooling benefits of trees are most significant. To achieve this, the following meteorological conditions have been defined: data will only be recorded on summer days with little wind (≤ 1,5 m s-1), clear to almost clear skies (degree of cloud cover ≤ 1/8) and a temperature of at least 25 °C (refer to Fig. 3) [Geib & Henninger 2023, p. 44].

Figure 3: Overview of the objects and conditions of the investigation [Geib 2023].

4.4 Data collection

The surface temperature of the tree canopy is measured by using a thermal imaging camera (refer to Fig. 4). The study examines three specific perspectives of the tree canopy: the side facing the house façade, and the east and west sides of the tree canopy [Geib & Henninger 2023, p. 44]. These perspectives are chosen to capture potential temperature variations caused by solar radiation and prevailing winds. By analysing these different perspectives, it is possible to infer a possible correlation between the surface temperature of the tree crown and the building facade. However, it is important to note that it is not always possible to obtain measurements from all canopy perspectives. This may be due to several factors, such as private property restricting access, business premises being closed on weekends, or varying distances from the building facade. These limitations can affect the comprehensiveness of the data collected. Nevertheless, efforts are made to ensure consistency in data collection.

In addition, thermal images of the surrounding buildings are taken to observe any response of their facades due to reflected radiation from the leaf surfaces. This step is essential to understand how the thermal properties of the canopy can affect nearby structures and contributes to a comprehensive analysis of microclimatic effects. All photographs are taken from a fixed position at each site, perpendicular to the wall, providing a standardised approach. Care is taken to ensure that canopy foliage has little or no contact with the wall surface, which could affect temperature readings.

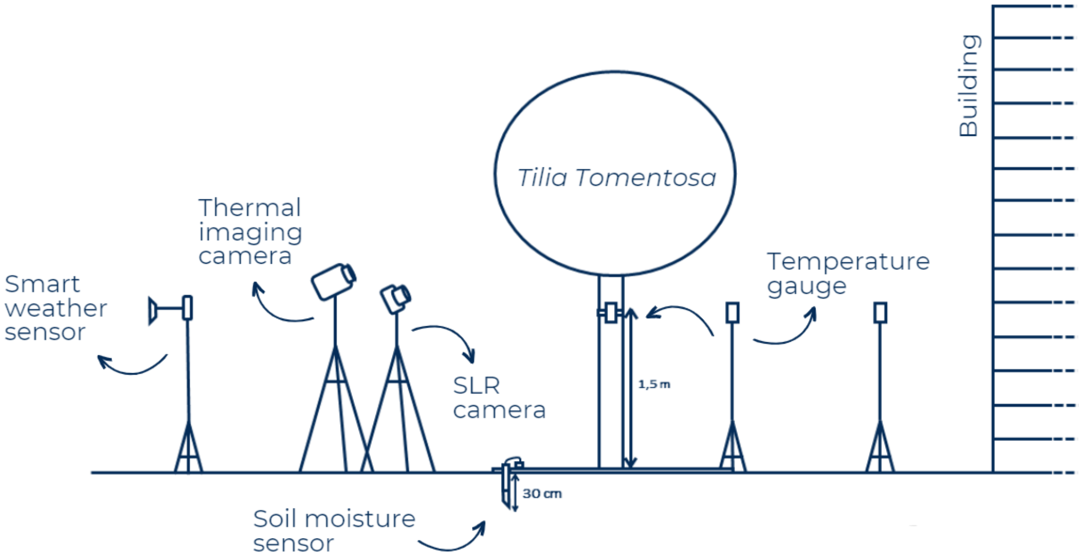

Figure 4: Outline of the experimental set-up; modified from [Geib & Henninger 2023, p. 44].

In addition to measuring the surface temperature of the tree canopy, three additional air temperature values are collected to analyse the effect of the crown temperature on the immediate environment. The first component measured is the air temperature just below the tree crown, at a height of 1.5 meters above ground level (refer to Fig. 4). This height is chosen because it is more representative of the human environment than the standard measurement height of 2 meters above ground [Souch & Souch 1993, p. 304]. During these measurements, the temperature sensor is protected from direct sunlight and placed in the shade to ensure accurate readings. Additionally, two further air temperature measurements are taken from the trunk of the tree towards the wall of the house (refer to Fig. 4). This approach aims to provide an accurate representation of the microclimatic effect in this particular area [Geib & Henninger 2023, p. 44]. These measurements will help to understand how the thermal behaviour of the tree affects its immediate surroundings, especially the building facade.

It may be beneficial to consider further environmental factors that can influence the surface temperature of the tree canopy. For example, weather conditions such as cloud cover, wind speed, and humidity can all affect the thermal behaviour of the trees. Incorporating these variables into the analysis could provide a more comprehensive understanding of the relationship between the tree canopy temperature and the building facade. Thus, the air temperature, air pressure, wind speed and direction, relative humidity, illuminance, and UV index are recorded at all locations during the measurement [Geib & Henninger 2023, p. 44].

To gain a full understanding of the impact of solar radiation, it is important to measure the temperature of the tree canopy at different times of the day. By collecting data during the peak hours of sunlight and in the evening, valuable insights can be gained into how building orientation and shading affect the thermal behaviour of the trees. To achieve this, measurements are taken at specific times throughout the day: early morning (07:00-09:00 UTC+1), midday/early afternoon (12:00-15:00 UTC+1), and late afternoon/early evening (17:00-19:00 UTC+1). These times are chosen because the measurements will be taken in the presence of the researcher. To avoid overloading the body with heat and to meet human needs, a continuous measurement period is not used.

It is important to note that subsequent analyses only compare measurements within individual trees. This is due to the uniqueness of each measurement site and tree, and the impossibility of replicating exact weather conditions. Therefore, comparisons will be made within each tree to understand its thermal behaviour throughout the day.

In addition to the field measurements, laboratory tests will be carried out to determine the maximum absorption of different leaf surfaces of the silver lime tree and reference trees. This will be used as a benchmark for optimal absorption performance and will allow comparison with measurements taken at street level. This approach will provide a detailed understanding of how different factors, such as solar radiation, building orientation, and leaf surface characteristics, affect the thermal behaviour of trees in urban environments.

A soil moisture sensor is used to measure the water content of the soil surrounding each silver lime tree. The moisture level is determined daily by measuring vertically through the soil profile to a depth of 30 centimetres (refer to Fig. 4). The sensor is placed in a shaded area, furthest away from the main trunk, to minimise the effects of direct sunlight and ensure a representative location for water uptake. As urban trees are increasingly planted in small tree discs, the furthest distance from the main trunk is limited to the size of that particular area [Geib & Henninger 2023, p. 44].

Close-ups of the leaves in the canopy are also used to record the rate and duration of leaf rotation to classify the temporal dimension [Geib & Henninger 2023, p. 44].

Figure 5: Insights into the setup at one of the locations; Buchenlochstraße, Kaiserslautern on 11 August 2023 [Geib 2023].

4.5 Spatial analysis and microclimate simulation

ENVI-met is a powerful tool for modelling microclimates at fine spatial scales. It provides visualisation tools to explain spatial patterns. Integration with AI and GIS platforms merges simulated microclimate data with spatial information about the study region [Mayer et al. 2024, pp. 1]. The TreePass module provides a comprehensive analysis of microclimate conditions to promote optimal tree growth and sustainability. It considers factors such as wind, light, and mechanical forces that affect trees, providing valuable insights for landscape architects, urban planners, and arborists. This information facilitates informed decisions on tree selection, location and maintenance strategies, improving the health, stability, and longevity of urban green spaces [ENVI-met 2024].

This study analyses the climatic effects of silver lime trees at different sites in Kaiserslautern using the ENVI-met software. The software assesses potential microclimate changes within a street resulting from an increase in the presence of silver lime trees or their exclusive planting. Furthermore, this study compares the climatic differences between a newly planted street with young silver lime trees and a street with middle-aged or older reference trees. The aim is to assess whether small silver lime trees have a greater cooling capacity than older comparator trees, which could be due to their ability to rotate leaves. With the help of the simulations, it can also be calculated how long it will take for newly planted silver lime trees to reach the same cooling capacity as the existing street trees. ENVI-met's research provides valuable insights into the impact of silver lime trees on local microclimates, contributing to a broader comprehensive understanding of their potential cooling effects in urban areas.

5 OUTLOOK

If the assessments indicate that the silver lime tree has a significant local or microclimatic impact on its immediate surroundings, recommendations for urban planning measures will be developed. These recommendations will be particularly useful in addressing the need for green or green-blue infrastructure in the context of urban redevelopment, with a focus on the use of public space, the selection of appropriate urban vegetation, and related design issues [Geib & Henninger 2023, p. 44]. In addition, these findings raise other issues such as financial considerations and the impact on the use of other tree species. Additionally, it is important to consider how trees and other vegetation interact with elements of the public realm and what measures can be taken to replace existing trees through replacement planting, even if this means accepting small saplings for an extended period. These issues are crucial for informing practical decisions in urban planning and landscape architecture, and highlight the importance of understanding the precise microclimatic impact of silver lime trees in shaping future urban environments. Although this study focuses on the silver lime tree for urban greening measures due to the specific research objectives and questions, extending the investigations to other tree species in future studies could help to gain a more comprehensive understanding of tree species selection in urban environments and possibly provide new insights into the ecological and economic impacts of different tree species. It is therefore recommended that further research is undertaken to explore the diversity of possible tree species for urban interventions and to make informed decisions.

The spatial arrangement of streets can significantly impact the relationship between green spaces and buildings, as it influences the area available for greening measures. In narrow or busy street areas, it can be difficult to find sufficient space to plant trees or create green strips. This can lead to an imbalance in the relationship between green spaces and buildings and limit the development of green structures. In addition, urban planning factors such as the alignment of the street, the density of the buildings, and the existing infrastructure play a crucial role [Ali-Toudert & Mayer 2006, pp. 751]. An unfavourable location of the street in terms of solar radiation, wind conditions or air quality may affect the suitability of certain tree species or greening measures. It is therefore important to consider the specific conditions of the street location in urban planning and greening projects to enable the effective integration of green spaces in urban areas and to ensure a balanced distribution of green structures. Furthermore, the integration of nature-based measures, such as increasing the size of tree grates, unsealing pavements and incorporating sponge city concepts into urban planning, can significantly enhance urban greening efforts and improve the resilience of cities to the impacts of climate change [Knapp & Dushkova 2023, pp. 187].

In addition, based on the results obtained near buildings, conclusions can be drawn about the usefulness of silver lime trees as roadside greenery. In particular, the assessment will consider whether the reduction in ambient temperature around the tree is effectively counteracted by the change in albedo. This assessment is important to understand the complex relationship between vegetation and built structures and to make informed decisions about the selection and placement of urban greenery to achieve desired climatic benefits while minimizing undesired outcomes. Incorporating these factors into urban planning and design processes is essential for creating sustainable and climate-resilient urban environments.

6 CONCLUSION

Cities play a crucial role in urban planning by influencing decisions that affect adaptation strategies. This includes setting standards for existing and new structures to increase their resilience to climate stressors and creating green and blue infrastructure to reduce the impact of extreme weather events. Municipalities are also responsible for developing plans to protect vulnerable populations and critical infrastructure during such events. These activities are crucial to increasing urban resilience and protecting the long-term development of cities from the impacts of climate change.

Adapting to climate change is not only feasible but more cost-effective than doing nothing in the long run. Urban areas are specifically vulnerable to the impacts of climate change. However, implementing good adaptation techniques can significantly reduce these risks. Strategic tree planting is an important aspect of urban adaptation. This requires detailed planning and careful selection of tree species to avoid additional costs associated with poor species selection and to minimise any drawbacks. This includes assessing species-specific cooling effects, adaptability to local temperature conditions, and long-term maintenance requirements. This way, cities can optimise their investment in urban greening projects while increasing their resilience to the effects of climate change. In addition, the use of climate-resilient tree species can bring many benefits to the urban environment, including improved microclimate conditions, better water management, and higher air quality. Furthermore, the presence of climate-tolerant trees helps to increase habitat supply, reduce vulnerability through biodiversity, and improve the overall living environment.

To effectively adapt to climate change, it is important to link existing policies with climate-friendly objectives and to ensure that investments are resilient to climate impacts. This requires integrating adaptation measures into existing policies to ensure coherence and synergy while reducing the possibility of counterproductive actions. At the city level, adaptation measurements are supported by a comprehensive and multidisciplinary approach that encourages cooperation with neighbouring municipalities, regions, and member states.

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