EFFECT OF BLUE-GREEN ROOFS ON OUTDOOR TEMPERATURE IN THE CITY OF AMSTERDAM

Colophon

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1. Introduction

The climate is changing. The increase of global temperature brings more and more extreme weather, including more frequent and longer lasting heatwaves. In only the past four years, the Netherlands has experienced the first and the third warmest summer in history – 2018 and 2019, respectively - and the longest heatwave in history – August 2020 (KNMI, 2021). Such extremes are expected to become more frequent in the future (IPCC, 2021).

During hot summer days, the situation in cities is often even worse than in rural areas. The temperature in Dutch cities can be up to 5,3 °C higher than in their rural surroundings (Steeneveld, 2011). This phenomenon is called the Urban Heat Island and describes the fact that cities often experience higher air temperatures than their rural surroundings. An efficient way to combat this additional heating of cities is to introduce more vegetated surfaces. However, space is very scarce in cities and finding locations for new green areas is often challenging.

One of the prominent – and often unused – surface cover types in cities are rooftops. They can make up to 60% of the total surface cover of a neighborhood (historical center (Kleerekoper, 2017)). Nowadays, roofs are mostly covered by black bitumen, gravel, or rooftiles; all materials which can store much more energy than vegetation due to their relatively high heat capacity.

Another proposed solution for utilizing the rooftops as a cooling element of a city are blue-green roofs. This report looks at the potential contribution of blue-green roofs to the climate on a neighborhood to city scale during hot summer days. This perspective is then later specified for the city of Amsterdam.

To assess the full potential of blue-green roofs, which is the aim of Resilio, we need to look at their benefits when it comes to smart water management, the potential increase in biodiversity in cities, creating attractive cool spots, and also at their impact on city-wide temperature particularly during hot summer days. To reach the latter objective we need to answer the question:

> ***What is the influence of blue-green roofs on the air temperature on the neighborhood and the city scale in summer?***

In short: What is the effect of blue-green roofs on the Urban Heat Island effect?

The question has been answered in three steps. First, we have conducted a literature review, which summarizes articles on blue-green roofs, and articles on measuring and modelling well-watered green roofs. In the second step we analyzed the area suitable for implementing blue-green roofs in Amsterdam and used this and the literature review to estimate a perspective of what the potential maximum cooling effect could be for the city of Amsterdam. In the last step, we have conducted an expert session on 20th January 2022 to discuss the results of the literature study and to evaluate the potential for blue-green

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roof implementation in the city of Amsterdam. The results of these three steps will be described in the following chapters.

2. Literature perspective

Literature about blue-green roofs as defined in the Resilio project is relatively scarce. When looking at research about blue-green roofs, the recent literature has been predominantly focusing on the potential of blue-green roofs for smart water management (Busker, 2022; Shafique M. K., 2016; Pelorosso, 2021; Versini, 2018). Articles focusing on the effect on outdoor climate are much more scarce and mostly only focus on the roof surface temperature (Shafique M. K., 2017) or its evaporative potential (Cirkel, 2018). Nonetheless, the background in which blue-green roofs contribute to better urban climate is based on atmospheric physics and is therefore well understood.

On the other hand, there is a broad spectrum of articles published about green roofs and all their potential benefits. The effect of green roofs has been both measured and modelled in various climates with prevailing literature from warm climates, both arid (e.g. (Razzaghmanesh, 2016)) and tropical (e.g. Singapore (Li X. X., 2016)). In this report, we focus on articles from areas that experience similar summer conditions as The Netherlands. Table 1 presents an overview of such articles used in this literature study.

2.1 Physical background

Since its first discovery of the Urban Heat Island (UHI) for the case of London in 1820 (Howard, 1820), a lot of research has been done into the origin of the phenomenon and how to reduce it. In general, the UHI is created by a different energy balance in a city than in a rural area (Wallace, 2006). The unique geometry and material use of cities cause them to store more heat in its surfaces, which then in response radiate more heat to their surroundings. On top of that, due to the lack of vegetation and water, the portion of the energy used for evaporation and transpiration is smaller. Many scientist have concluded that the best way to decrease the UHI is to increase the percentage of vegetation in urban areas and therefore bring them closer to their natural surroundings (Gunawardena, 2017).

In general, blue-green roofs cool the urban environment by influencing the energy balance of the city. Solar energy that enters the city is partly reflected by the surfaces back to space. The rest is either used by plants to transpire, do photosynthesis and by water evaporating or it is used to heat up the air and the surfaces. If a bigger part of the solar energy is used by the plants, there is less energy left for heating up the surfaces and the air of the city. The energy used by the plants together with the energy used for open water evaporation is often referred to as the latent heat, meaning “hidden” heat and therefore not experienced by the inhabitants.

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	author	location	time	effect	setup	model	scale
	Santamouris (2014)	Chicago, US, New York, US, Tokyo, JP, Hong Kong, CN		0.3 - 3 °C			
modelling	Li (2016)	Singapore	night average	1 °C	near-surface air temperature	WRF	city
			max at 2:00	2 °C			
	Smith (2011)	Chicago, US	19:00- 23:00	2 -3 °C	2m air temperature	WRF	city
	Li (2014)	Baltimore-Washington, US	night time maximum	1 °C for 100% green roof fraction, 0.3 °C for 30%, negligable effect below 10% green roof fraction	2m air temperature	WRF	city
				dry condition to cooling by 1 °C for moist conditions			
	Peng (2013)	Hong Kong, CN	14:00	0.4 - 0.7 °C	pedestrian-level air temperature	ENVI-met	neighborhood
	Lalošević (2018)	Belgrade, RS	summer mid-day	0.1 - 0.37 °C depending on the neighbourhood typology	1.8 m air temperature	ENVI-met	neighborhood
	Busker (2022)	Amsterdam		80% evaporative potential for blue-green roofs vs. 17 % for green roofs	evaporation performance	hydrological model	
measurements	Cirkel (2018)	Amsterdam, NL	year average	in 111 mm/year water shortage for sedum plants	evaporation performance	hydrological model	
				30 mm water storage results in 55 mm/year shortage			
				80 mm water storage results in 15 mm/year shortage			
	Smalls-Mantey (2021)	New York, US	daytime	max 1.8 °C	3 m air temperature		street
	Köhler (2019)	Berlin, GR	20-year UHI change	UHI stabilization effect of 1.5 °C over the past 20 years	UHI effect		city
	Heusinger (2015)	Braunschweig, GR	August 15:00 average	0.7 °C	3 m air temperature		street
	Solcerova (2017)	Utrecht, NL	average over 24 hours	0.2 °C increase	air temperature 15 and 30 cm above the roof		roof
			nighttime cooling effect	0.5 °C			

Table 1 Overview of relevant literature used in this study

Researchers from the Wageningen University showed that every 10 percent points increase of green surfaces in a city decreases the air temperature by approximately 0,5 °C (Van Hove, 2015). This study uses both modelling and measurements in several Dutch cities to show how changes in surface cover can influence the temperature on a city scale. The resulting connection between increase in percentage of green surfaces and decrease in air

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temperature became a rule-of-thumb for potential effects of additional greening, and it was also used as a base for one of the heat resilient guidelines for Dutch cities (Kluck, 2020).

Even though blue-green roofs are located several meters above the street, they can theoretically have a temperature effect at pedestrian level. This is due to the air dynamics of the so called boundary layer (Oke, 1987). The boundary layer is the lowest part of the atmosphere that is directly influenced by the earth's surface. During a day, the surface heats up which then consequently heats up the air just above the surface. Warm air then rises and is replaced with colder air from above which causes mixing. Therefore the boundary layer is often referred to as the “mixed layer”, meaning the temperature is more or less the same throughout the whole layer.

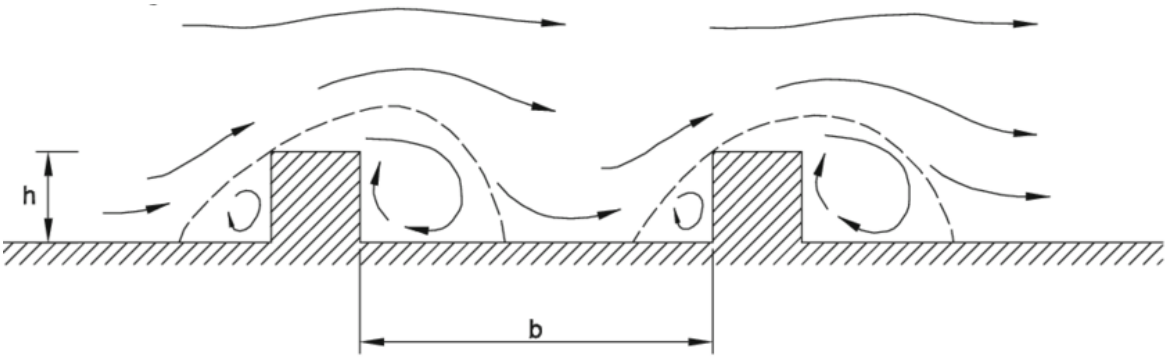

Figure 1 Air flow regimes associated with different urban geometries (Oke, 1987). As visible from the figure, the mixing of air from above the roof layer down to the street layer is dependent on the combination of the width of the street (b) and the height of the buildings (h).

Due to the mixing effect of the boundary layer, changes of the surface anywhere in the city – pedestrian or roof level - will influence the temperature in the whole layer. Therefore, blue-green roofs can in a sense also affect the temperature at the pedestrian level (Figure 1). However, as the boundary layer can reach up to 2 km height during a warm summer day (Wallace, 2006), the volume of air that experiences the influence is quite large. As a result, it is logical that the effect of one roof might not be noticeable at pedestrian level, even when the cooling at that particular roof is strong.

2.2 Types of vegetated roofs

There is an abundance of modelling and measurement studies published from all over the world focusing on various types of green roofs (Andenæs, 2018; Santamouris, 2014). The strongest effect on urban climate was measured for *intensive green roofs* with a thick layer of substrate and higher level vegetation like trees and bushes. Green roofs with intensive vegetation, also known as roof gardens, are relatively common in countries such as Singapore. Modelling research shows very promising results when it comes to cooling potential of intensive green roofs; maximum nighttime difference at pedestrian level 2 °C (Li X. X., 2016). However, these roofs are very rare in the Netherlands and in Europe in general. This is due to their high weight which makes them almost exclusively suitable for

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newly constructed buildings that are constructed for such a heavy roof. In Europe, green roofs are much more often used as an add-on to already existing buildings, which decreases their maximum possible weight to the baring capacity of the already existing roof.

The most common green roofs in Europe are so called *extensive green roofs*. These roofs have a shallow substrate layer (up to 20 cm, but often no more than 5 cm) and are often covered with sedum type plants (Berardi, 2014). These plants can withstand longer periods of droughts, which is necessary due to the limited water storage capacity in the rootzone (the substrate layer) of such green roofs. When it comes to research on the effect of roofs on city climate in Europe, we can mostly find articles focusing on this type of roofs.

The third type of vegetated roofs that is becoming more common in Europe are the *blue-green roofs*, the focus of this study. Blue-green roofs can be covered with higher type of vegetation, similar to the roof gardens in Singapore, but also simply by sedum plants. Blue-green roofs with sedum plants will be the focus of this study as it is the most common type of blue-green roof currently used in Amsterdam and in the Resilio project.

2.3 The temperature effect of blue-green roofs

Blue-green roofs have grown in popularity during the recent two decades particularly due to their capability to store rain water better than conventional green roofs. The higher storage capacity of blue-green roofs and its benefits have been measured and investigated all over Europe and the world (Pelorosso, 2021; Shafique M. K., 2016; Versini, 2018).

Effect of blue-green roofs on urban climate has however been studied to much lesser extent. Several studies look at the effect of blue-green roofs on indoor climate or energy consumption in the building, which might consequently lead to an effect on the city climate (e.g. by decrease in use of air conditioning). Some studies then focused on the reduction of surface temperature of the roof. Shafique et al. (2017), for example, showed that the surface temperature of blue-green roofs is 5 – 9 °C lower than the temperature of a control roof. Nonetheless, only very few studies have looked at the potential effect for cooling the air temperature.

Busker (2022) showed that, when it comes to mitigation of high temperatures in urban area, blue-green roofs have undeniable advantage compared to green roofs especially during drought. After an extended period of drought, the water storage in the substrate of regular green roofs gets depleted and the evaporation drops only to 17% of the potential evaporation of sedum plants. If a water retention layer is present under the substrate, the sedum plants keep evaporating at almost 80% of their potential.

The high evaporative potential of blue-green roofs was also measured in 2017 in Amsterdam (Cirkel, 2018). Results of this study show that blue-green roofs have better evaporative properties than green roofs without a water layer. Good evaporation of the plants is important because it is the proxy to the cooling efficiency of vegetation. When a water storage of only 30 mm is added to a conventional green roof, the amount of water

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shortage for sedum type plants drops from 111 mm/year to 51 mm/year. The water shortage reduces even further, to only 15 mm/year, for the potential storage of 80 mm.

Both measurements and modelling predicted a beneficial effect of blue-green roofs on urban climate due to higher potential evaporation rates. Data from these studies (Busker, 2022; Cirkel, 2018) can work as an input to climatological models showing the effect of blue-green roofs (added benefits compared to green roofs) on urban climate and their added benefits compared to traditional green roofs. However, the literature body on blue-green roofs on urban climate specifically is still very limited. Therefore, to objectively assess the potential effect of blue-green roofs on the city scale, we extended the search and also include literature focusing on well-watered green roofs.

2.4 The temperature effect of well-watered green roofs

Several *modelling* studies focusing on sedum covered green roofs show a potential of 2-3 °C cooling during the evening hours if the whole city is covered with green roof (Smith, 2011). However, the *measured* air temperature effect of sedum covered green roofs is shown to be relatively low to none, maximum of less than 0.2 °C (Solcerova, 2017).

The relatively high cooling effect predicted by models is in contrast to the measurement studies and seems to come mostly from the assumptions taken by the models, e.g. homogeneity of the streets, building sizes, and physical properties of the buildings, or an expected constant rate of evaporation. One of the most common assumptions is that green roofs are well-watered and well-transpiring. This is however only realistic for several days after a rainfall. According to Cirkel et al. (2018), sedum transpires 3 mm/day. With water storage of 25 mm in the substrate (50% water holding capacity in 5 cm substrate layer (Zhang, 2019)), the plants only have 7 days of unhindered evaporation after which they will start saving water and the cooling effect will diminish.

The importance of water availability for plants connected to the cooling potential of the roof has been modelled by, for example, Li et al. (2014). The cooling rapidly decreases with lower soil moisture. For well-watered conditions, the cooling effect on a city scale is 1 °C, if all roofs are covered with vegetation. This cooling drops with the predefined soil moisture, and for very dry conditions the model results even show a slight increase in the average air temperature in the city (+0.3 °C).

Modelling studies of well-watered and well-transpiring green roofs show the best case scenario and are therefore too positive for a realistic assessment of sedum covered green roofs. However, with an additional water storage below the sedum layer, such as seen in blue-green roofs, the plants would receive sufficient moisture much longer than the calculated one week. We can therefore argue that the published body of articles regarding well-watered and well-transpiring green roofs is more representative of blue-green roofs.

2.4.1 Modelling of well-watered green roof

Results of modelling studies on green roofs show a maximum reduction of the air temperature between 0.3 and 3 °C (Santamouris, 2014). This is a quite high range that is

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connected to the modelled climate, the percentage of roofs covered by a green layer, the evaporative capacity of the vegetation, the height or location at which the temperature is modelled (above the roofs vs. pedestrian level) and many other aspects.

A study by Li et al. (2014) shows a potential cooling effect of well-watered green roofs of 1 °C. This pedestrian-level cooling effect is a result of a scenario when 100% of the roofs is converted into well-watered green roofs in a city with 25% (residential neighborhoods) to 50% (city center) of the total surface area covered by roofs. The cooling effect drops with decreasing percentage. For model runs with 30% coverage the effect drops to 0.3 °C and for 10% and less coverage the effect becomes negligible.

Even though the air is relatively mixed through the whole city, different neighborhoods experience a slight variation in the air temperature due to their unique characteristics (street orientation, building height, street width). One of these characteristics is the presence of green roofs in the neighborhood. According to Peng & Jim (2013), low rise urban form - typical for many residential locations in Amsterdam – can benefit the most from green roof implementation. For this type of neighborhood, the cooling at pedestrian level reaches a maximum of 0.7 °C if all the roofs (34% of the total area) are covered with sedum plants. For similar setting and model, Lalošević et al. (2018) show a cooling effect on pedestrian level of up to 0.3 °C. Nonetheless, these are maximum cooling potentials reached in the studies. The cooling for specific times and locations in the modelled neighborhoods vary and often show no change at all.

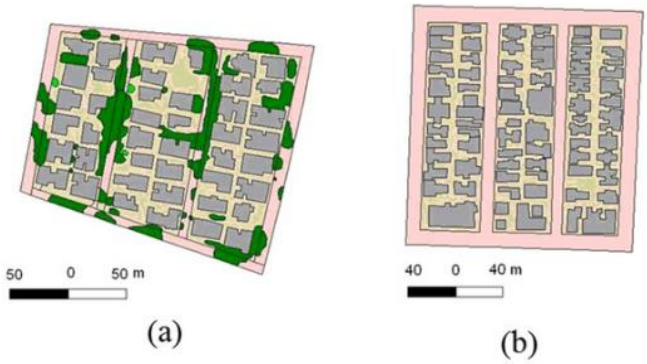

Figure 2 Neighborhood configurations best suited for implementation of green roofs. a) open-set low rise - building height 10m, plot ratio (built-up/non-built-up area) 1.8, vegetation 18%, roof area 34%, b) compact low-rise - building height 15m, plot ratio (built-up/non-built-up area) 3, vegetation 0%, roof area 34%. (Peng, 2013)

2.4.2 Measurements of green roofs

Measurement approaches that investigate the effect of green roofs on urban climate are much less common than modelling. This is mostly due to the fact that there are not many cities where green roofs are the dominant roof cover. This means that measurements done at a certain roof are always limited to the effect of the roof to its direct surroundings. Measuring the effect on city scale is not possible as the effect of one single roof is expected to be negligible on city scale, and as it is not feasible to set up a measurement

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plan to measure the effect of many roofs. Therefore, the effect of one roof always needs to be extrapolated to the whole city, for which a model is necessary. For this reason, most measurement studies focus on temperature reduction directly above the roof or look solely at surface temperature reduction.

Measurements of very large (2.7 ha) green roofs show a relatively strong effect on the local air temperature. The maximum daytime air temperature difference measured above a black roof and a green roof in New York was 1.8 °C (Smalls-Mantey, 2021). However, a study from Germany focusing on relatively small (600 m^2) green roofs, shows only 0.7 °C average difference in August for 3p.m. (Heusinger, 2015). This number drops if green roofs are compared to gravel roofs instead of black bitumen. A case in Utrecht (NL) shows a cooling effect of less than 0.5 °C for well-watered roofs (Solcerova, 2017).

2.5 Conclusion of the literature review

The reviewed studies show a small cooling effect of (blue-)green roofs on urban environment for all scales. When considering the ideal situation (100% roofs covered with well-watered vegetation), the cooling effect at pedestrian level on a *city scale* reaches values up to 1 °C when compared to gravel roofs. Similar results are found in studies focusing on *neighborhood scale*, 0.3 – 0.7 °C. The lower values for neighborhood scale are mostly caused by lower number of roofs (34% of total area) compared to the city scale model (25-50% of total area).

There are many factors influencing the effect of green roofs on neighborhood to city scale from which the available roof percentage and soil moisture appears to be important factors. The review studies show that with less green roof cover the cooling effect decreases and is negligible for values below 10%. All reviewed studies also agree that with lower availability of water to the plants, the cooling effect decreases. This is a very strong argument pointing towards the benefits of blue-green roofs in comparison to green roofs without water storage.

3. Amsterdam perspective

The literature review suggest that if all roofs in a city were to be equipped with a blue-green layer, the total cooling might potentially reach 0.3 to 1 °C. However, not all roofs are always suitable for such a construction. If we look specifically at Amsterdam, many houses have pitched or gable roofs. On top of that, roofs with many smaller parts that connect to each other result in a too low ratio between surface area and perimeter of the roof. The surface of such roof is too interrupted by chimneys and air conditioning systems or consists of small areas with many protrusion which is not suitable for implementation of the blue-green roof system. Proper functioning of a smart water management system requires namely a minimum area of 200m^2. Other parameters might also come into play, such as the carrying capacity or the age of the buildings. The details will not be discussed here; the full method behind choosing the suitable roofs is described in detail in Resilio deliverable 6.3 Water (2022 in prep.).

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The resulting area of roofs in Amsterdam that can be potentially used as blue-green is 6 km^2. The city area of Amsterdam is ca 132 km^2, which means that approximately 4,5% of the area of Amsterdam is suitable for future blue-green roof development. This percentage does not seem very high, but it translates to 27% of the total roof area in Amsterdam. Considering that Amsterdam is a historical city with many pitched roofs, it is an surprisingly positive result. This percentage can further decline if, for example, only buildings constructed after 1960 are taken into consideration. For this case, the percentage of suitable roofs would drop to 22% (Haer, 2022 in prep.).

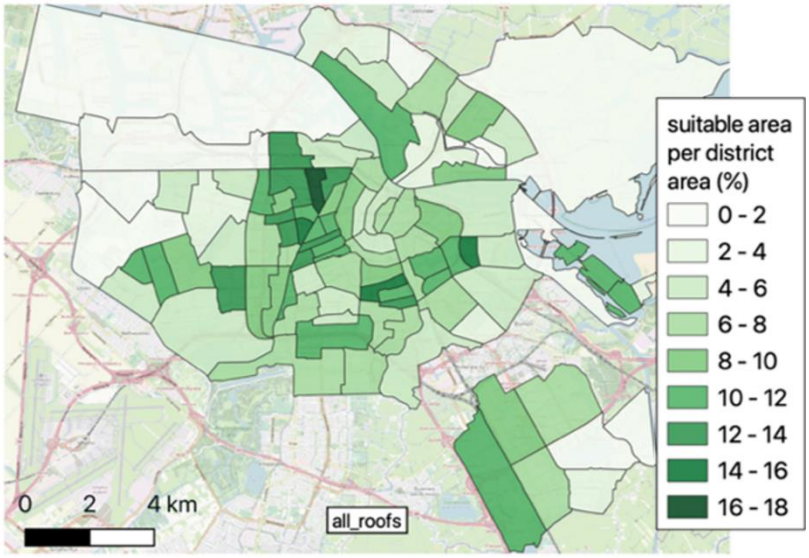

Figure 3 Percentage of suitable roofs for blue-green roof construction in Amsterdam (shown as % of total district area). For this analysis, only non-flat roofs and roofs with too high complexity were excluded. (Haer, 2022 in prep.)

If we compare the maximum potential percentage of blue-green roofs in Amsterdam (27%) to the literature, we can find some first indication of the cooling effect that can be delivered by these roofs.

Li et al. (2014) shows, based on model runs, a cooling effect of 0.3 °C if 30% of the rooftops in a city is replaced with well-watered vegetation. These model runs are relatively similar to Dutch cities, with 5-10 m heigh buildings and between 5 and 50% green cover at the street level, depending on urban typology. However, the research considers an average roof cover percentage of 25 to 50% of the total surface area of the city (representative for Washington, US). In Amsterdam, most residential neighborhoods have 13-20% of rooftop cover (Kleerekoper, 2017). Therefore, the actual effect is expected to be lower than the 0.3 °C.

Another way of analyzing the effect is by looking from the perspective of potential additional green surface in the city of Amsterdam. As mentioned above, the roofs potentially suitable for blue green roof implementation cover 4.5% of the total area of Amsterdam. The rule-of-thumb introduced in Van Hove et al. (2015) states that every 10

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extra percentage points of green surface in a city can be translated to ca. 0.5 °C cooling. By applying this relation to Amsterdam we see that the additional 4.5% of green surface can lead to ca. 0.2 °C air temperature cooling on a city scale.

4. Expert opinion

4.1 Introduction

In order to critically evaluate the results of the literature review and the perspective for Amsterdam, an expert session was organized on the 20th January 2022. The goal of this session was to assess the effect of blue-green roofs on the street-level air temperature in a city like Amsterdam for a summer situation.

The experts participating in this session were from various disciplines and provided a broad spectrum of points of view related to blue-green roofs, urban climate, (micro)meteorology, and modelling. Their names and expertise can be found in Table 2.

Table 2 List of experts with their affiliation and their specializations; in alphabetical order.

Emma Daniels, PhD *(former KNMI)*	Urban climate modelling Effect of vegetation on city level climate
Olivier Hoes, PhD *(TU Delft)*	Urban hydrology Measurements of blue-green roof effect on building level
Cor Jacobs, PhD (RIVM)	Micrometeorology, urban climate Relationship between evaporation and heat
Lisette Klok, PhD *(HvA)*	Meteorology, urban climate Urban heat adaptation in public areas
Jeroen Kluck, PhD *(HvA)*	Climate adaptation in cities
Merle van der Kroft, MSc *(Metropolder Company)*	Blue-green roofs expert Advisor at MetroPolder Company
Natalie Theeuwes, PhD *(KNMI)*	Meteorology, urban and neighborhood climate modelling Effect of water and vegetation on city climate

The focus of the session was split into two major topics:

1. the effect of blue-green roofs on the city of Amsterdam as a whole
2. the variation in the effect for different types of neighborhoods

During the first part of the expert session, the literature review was presented to the panel of experts and the discussion focused on estimating a realistic effect of blue-green roofs. In the second part, the expected climate effect of blue-green roofs was scrutinized from the point of view of various neighborhood typologies in Amsterdam with focus on the different heights of buildings and widths of streets. The following section summarizes the outcomes of the session.

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4.2 Outcomes

When it comes to *the effect of blue-green roofs on the whole city of Amsterdam*, the experts agreed that the determining factor is the availability of roofs suitable for blue-green roof implementation in combination with the total percentage of the roof surface area compared to city. The effect suggested in Li et al. (2014) (0.3 °C for 30% of green roofs in a city with 25-50% roof cover) was agreed to be realistic as the maximum potential cooling. Consequently, given the relatively low roof cover percentage of the total area of Amsterdam (20% (CBS, 2021)), the experts agreed that the cooling effect will be in most instances lower than the maximum 0.3 °C. Several of the experts also pointed out that the rule-of-thumb (10 percent points of extra green leads to 0.5 °C, Van Hove et al. 2015) very well agrees with the numbers from the literature. Interestingly, this rule was developed for influence of additional vegetation at pedestrian level; the effect of green (blue-)green roofs was not taken into account.

When it comes to *the effect on various types of neighborhoods*, the experts agreed that the general parameters such as building height or width of streets will play a role in the resulting cooling effect. Neighborhoods with taller buildings and narrower streets are expected to benefit less from the presence of blue-green roofs than low-rise neighborhoods with broad streets (effect shown in Figure 1). The difference between neighborhoods is quite significant in modelling studies as cooling effects in some neighborhoods might be twice as high as in other neighborhood (Lalošević, 2018; Peng, 2013). However, in the perspective of cooling efficiency at pedestrian level, the experts agreed that doubling a small temperature reduction (e.g. 0.3 °C to 0.6 °C) does not lead to substantially more cooling in a neighborhood as both temperature changes are too small to be noticeable by the residents.

To experience *a noticeable effect* of blue-green roofs, we would have to zoom-in to a smaller scale. During the discussion, a point was made that the results of most of the studies are averages over the whole neighborhood/city. The cooling effect of blue-green roofs can reach higher values when measured right above the roof self. This can be beneficial for the residents of the building, if given access to the roof.

Besides a cooling effect in its direct surroundings, implementation of (blue-)green roofs might have an *indirect temperature effect* on the city climate by reducing the heat expelled by air conditioning. Results from Resilio WP6.3 indicate a potential cooling effect of blue-green roofs on the indoor air temperature. This indoor cooling can potentially limit the use of air conditioning in buildings and therefore decrease the anthropogenic heat flux influencing the total energy balance of the city, decreasing the urban heat island effect.

All the experts agreed on the conclusion that the effect of blue-green roofs on the climate of Amsterdam is potentially very small to negligible. However, the experts also agree that this should not be a discouraging factor for implementation of blue-green roofs in general. There are *many other potential benefits of blue-green roofs*, ranging from indoor cooling

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to urban water management, quality of life in the city or biodiversity, which are all good reasons to aim for more blue-green roofs in cities.

5. Conclusions

Results of both the literature review and the expert session show that the temperature effect of blue-green roofs on the city of Amsterdam is very small to negligible, even if all suitable roofs were used. This is due to a combination of many factors, such as the fact that the temperature effect is mixed up in the boundary layer and that the magnitude to which the air temperature can be cooled only by evaporation is limited. On top of that, the low availability of suitable roofs played an important role. 27% of the total roof area was suitable for implementation of blue-green roofs, which translates to only 4,5% of the surface area of Amsterdam. The city-wide effect was estimated to be smaller or equal to 0.3 °C at pedestrian level, with local variations up to 0.6 °C depending on the neighborhood typology. We conclude that this cooling effect is too small to be noticeable by the residents and therefore blue-green roofs are not proven to be an effective cooling solution for urban heat.

Nonetheless, blue-green roofs provide an option to extend the greening initiative to surfaces that are at this moment largely left unused – the rooftops. As such, blue-green roofs are a part of the overall greening initiative, a part that has not been fully exploited yet. We should also not forget other potential benefits of blue-green roofs, ranging from indoor cooling to urban water management, quality of life in the city or biodiversity.

Future research could focus on the cooling effect of blue-green roofs on the very local scale: on the roof self and inside the building. Lower temperatures on the roof open a possibility for creating private green spaces for the residents of the building and consequently increasing outdoor thermal comfort during hot days. Furthermore, decreasing indoor temperature in the residential areas under the roof can possibly decrease the use of air conditioning. This might lead to an indirect cooling effect of the blue-green roofs on urban environment by decreasing the anthropogenic heat load.

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Image 1 - Fotographer: [A. Example]

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