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Urban heat stress mitigation potential of green walls: a review

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URBAN HEAT STRESS MITIGATION POTENTIAL OF GREEN WALLS: A REVIEW

Abstract

Cities with resilience to climate change appear to be a vision of the future, but are inevitable to ensure the quality of life for citizens and to avoid an increase in civilian mortality. Urban green infrastructure (UGI), with the focus on vertical green, poses a beneficial mitigation and adaptation strategy for challenges such as climate change through cooling effects on building and street level. This review article explores recent literature regarding this considerable topic and investigates how green walls can be applied to mitigate this problem. Summary tables (see additional information) and figures are presented that can be used by policy makers and researchers to make informed decisions when installing green walls in built-up environments. At last, knowledge gaps are uncovered that need further investigation to exploit the benefits at its best.

1 Introduction

1.1 Environmental framework

Climate change is a serious problem that the world and its inhabitants face today. Its effect is strongly felt in - but is not limited to - cities, where, due to temperature rises, an intensification of the urban heat island (UHI) effect can take place, meaning that average temperatures in cities are higher than in surrounding rural areas (Oke, 1976; Arnfield, 2003). This temperature difference can be as high as 10°C (Pearlmutter *et al.*, 2017). The main causes of these high temperatures are anthropogenic heat sources and the increased absorption and re-radiation of heat by urban structures made of concrete, asphalt, metal etc. (Oke, 1976; Rizwan, Dennis and Liu, 2008), and the lack of green and blue infrastructure. The effect is greater at night, when buildings and roads cool down much more slowly than natural elements.

This can be detrimental to human health (Robine *et al.*, 2008; Gabriel and Endlicher, 2011) and, in addition, increase the energy demand for cooling systems (Ottelé *et al.*, 2011; Perini and Rosasco, 2013). The viability of cities can only be guaranteed if they become resilient to these increasing temperatures.

1.2 Green walls as a nature-based solution

Urban green infrastructure (UGI), referring to green walls, green roofs, urban trees and hedges, can contribute to reducing the impact of the urban heat island effect through cooling effects like shading and transpiration (Alexandri & Jones 2008; Norton et al. 2015; Pérez et al. 2011; Wong et al. 2010). Other ecosystem services provided by UGI are the capture of PM via deposition on leaves (Ottelé, van Bohemen and Fraaij, 2010; Sternberg *et al.*, 2010; Pugh *et al.*, 2012; Grote *et al.*, 2016; Weerakkody *et al.*, 2017), carbon sequestration (Perini and Rosasco, 2013; Pearlmutter *et al.*, 2017), the removal of gaseous pollutants such as nitrogen oxides (Tallis *et al.*, 2011), acoustic improvement (Wong et al. 2010; Veisten *et al.*, 2012), increased biodiversity (Madre *et al.*, 2015), increased ecosystem resilience (Demuzere *et al.*, 2014), water retention and purification, and social and cultural benefits (White and Gatersleben, 2011). These ecosystem services might also be under pressure in a changed climate (Samson *et al.*, 2019).

Green walls (GW) are often referred to in the literature as Vertical Greening Systems. They can be applied in situations where there is not enough space for other types of UGI, and are therefore effective in already congested cities. Green walls do not inhibit natural ventilation in street canyons, like other forms of UGI do, especially under certain building geometries and meteorological conditions (Litschke and Kuttler, 2008; Vos *et al.*, 2012; Jeanjean *et al.*, 2015). Moreover, the available vertical area of buildings is larger than the roof area (Raji, Tenpierik and Van Den Dobbelsteen, 2015) and not all roofs are technically suitable to support green roofs, while this is less of a problem for walls on which green walls can be installed. In this way, green walls can create many possibilities for urban planning towards reduced local temperature.

In general there are two types of green walls according to their growing type (Figure 1), namely green façades (GF) and living wall systems (LWS) (Köhler, 2008). Green façades (Figure 2 top and middle) consist of creepers rooting in the soil (in other words: these plants are soil bound) and climbing up the wall with (indirect system or double skin façade, idGF) or without (direct system, dGF) use of a climbing aid (e.g. frames or wires). GF are cheap, sustainable and require less maintenance compared to LWS. On the other hand, it can take years before the desired amount of green cover is reached. Furthermore, the choice of plants is limited, and there is a fear that green façades will damage building walls. However, this should not be a problem if the correct plant species and climbing aid are chosen for a specific situation.

For LWS (Figure 2 bottom), plants root in a substrate material directly attached to the wall. An LWS system consists of pre-cultivated panels, modules, planters, bags, textiles, etc. Two groups of substrate material can be distinguished (Figure 1). Inert substrates consist of purely mechanical structures in which plant roots can develop. Nutrients need to be added to the irrigation water to reach the vegetation. In contrast, organic substrates can provide some nutrients directly to the plants. Furthermore, an irrigation system is necessary to provide the plants with sufficient water and nutrients. With these systems, the end product can be seen immediately and a large variety of plant species are eligible (e.g. mosses, lichens, herbaceous plants, climbing plants and small shrubs) (Ottelé, van Bohemen and Fraaij, 2010). Moreover, when a plant dies, it is easily renewed. Disadvantages are the higher costs of installation and maintenance (Perini and Rosasco, 2013). Functional and regular maintenance are essential for this kind of system.

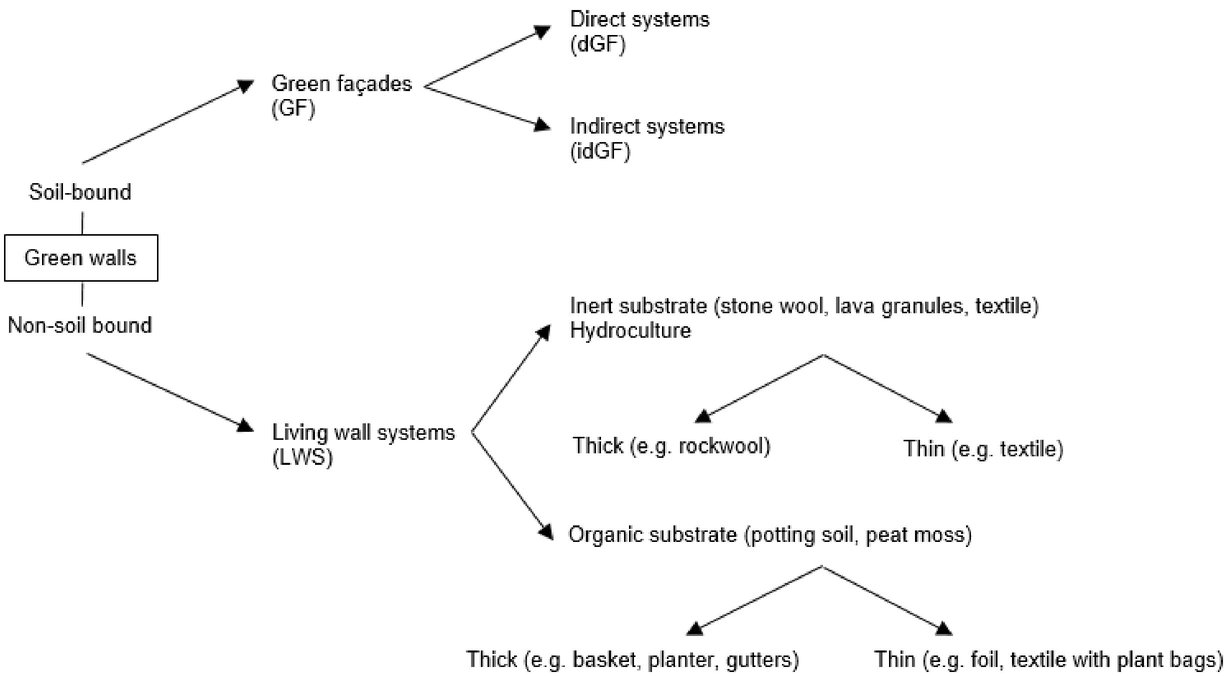
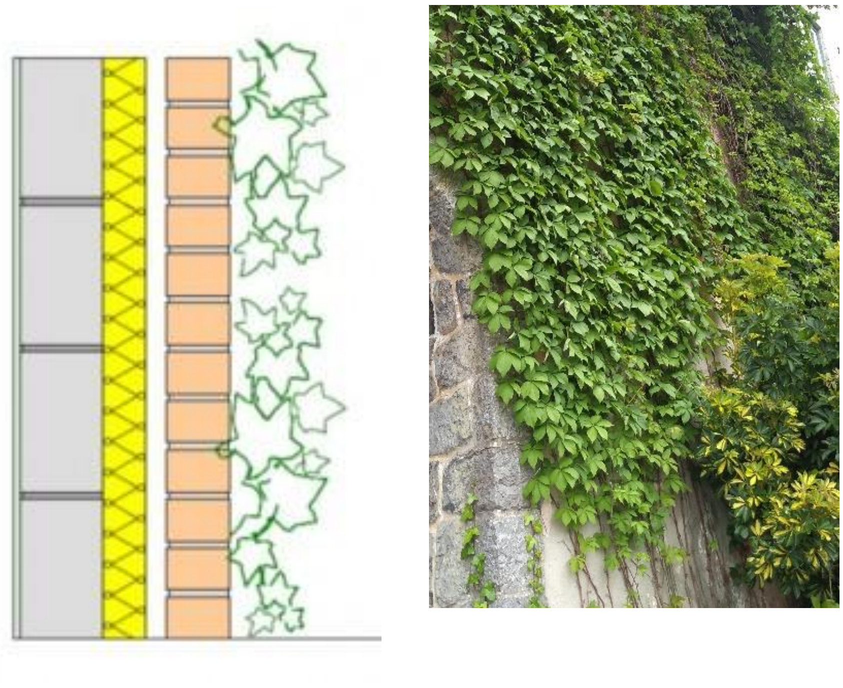


Figure 1: Classification of green walls.

A



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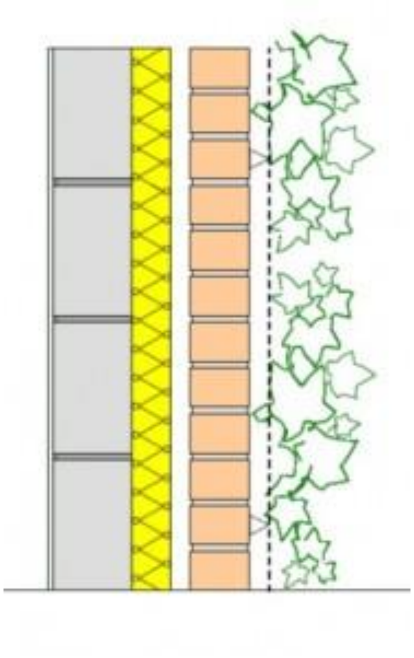

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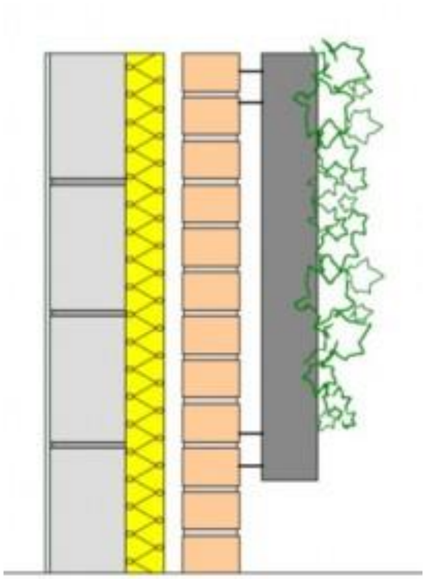
C



Source: www.gevelgroen.be

Figure 2: A: direct green façade, B: indirect green façade and C: living wall system.

1.3 Review strategy

In recent years many articles have appeared about green walls, the majority of them about their (hygro)thermal and cooling capacity. Most papers cover experimental research, but also model simulations, or combinations of both, and some review papers have been published. Nevertheless, an in-depth review on the mitigation potential of green walls for reducing heat stress has not yet been performed. With this review, we want to encompass a broad range of literature data to uncover the state of the art and future requirements for the use of green walls as a nature-based solution for local climate mitigation. Furthermore, a meta-analysis is conducted to assess the overall performance of green walls in terms of cooling (and heating). This review study is based on literature research considering scientific journal papers (published on Web of Science©) on the cooling effects of green walls, up to and including 2018. Papers about indoor vertical greening and hedge rows were excluded from the analysis.

2 Thermal and hygrothermal effects of green walls

The effect of vegetation on the local climate and its cooling potential for buildings have been extensively investigated in recent decades. Especially nature-based solutions, such as green roofs and green walls, have become of particular importance for both scientists and policy makers. The majority of articles on Web of Science© about green walls was somehow related to their thermal effects (Figure 3). Keywords were ‘green wall’, ‘green façade’, ‘vertical green’, ‘temperature effect’ and ‘cooling’. In addition, several review papers which contain information, among other things, about the thermal effects of green walls have appeared in recent years (Köhler, 2008; Sheweka and Mohamed, 2012; Demuzere *et al.*, 2014; Hunter *et al.*, 2014; Pérez *et al.*, 2014; Safikhani *et al.*, 2014; Norton *et al.*, 2015; Pérez-Urrestarazu *et al.*, 2015; Raji, Tenpierik and Van Den Dobbelsteen, 2015; Charoenkit and Yiemwattana, 2016; Besir and Cuce, 2018), but a meta-analysis taking the different climate types in to account has never been done before.

In this chapter the cooling mechanisms of green walls on the underlying building and on the local microclimate will be described. This is followed by a meta-analysis of published literature on the topic.

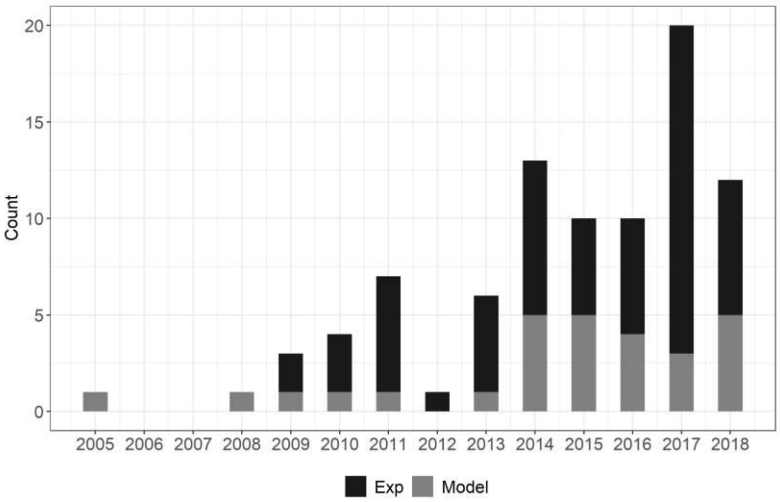


Figure 3: Number of published articles on Web of Science© describing experiments (Exp) and modelling studies (Model) about thermal properties of green walls (review articles not included).

2.1 Mechanisms behind thermal effects of green walls

Literature has shown that green walls can provide a flexible tool to decrease the temperature in urban environments and thus mitigate the UHI effect. They are able to lower the building wall, indoor air temperatures, ambient air temperatures and thereby increase thermal comfort for citizens and reduce the energy demand for cooling. In general, three effects that play a role in the cooling capacity of GW can be distinguished: (i) shading, (ii) evapotranspiration, and (iii) insulation and ventilation (Davis et al. 2015; Djedjig et al. 2016; Dahanayake and Chow, 2017) (Figure 4). These will be thoroughly discussed in the next paragraphs.

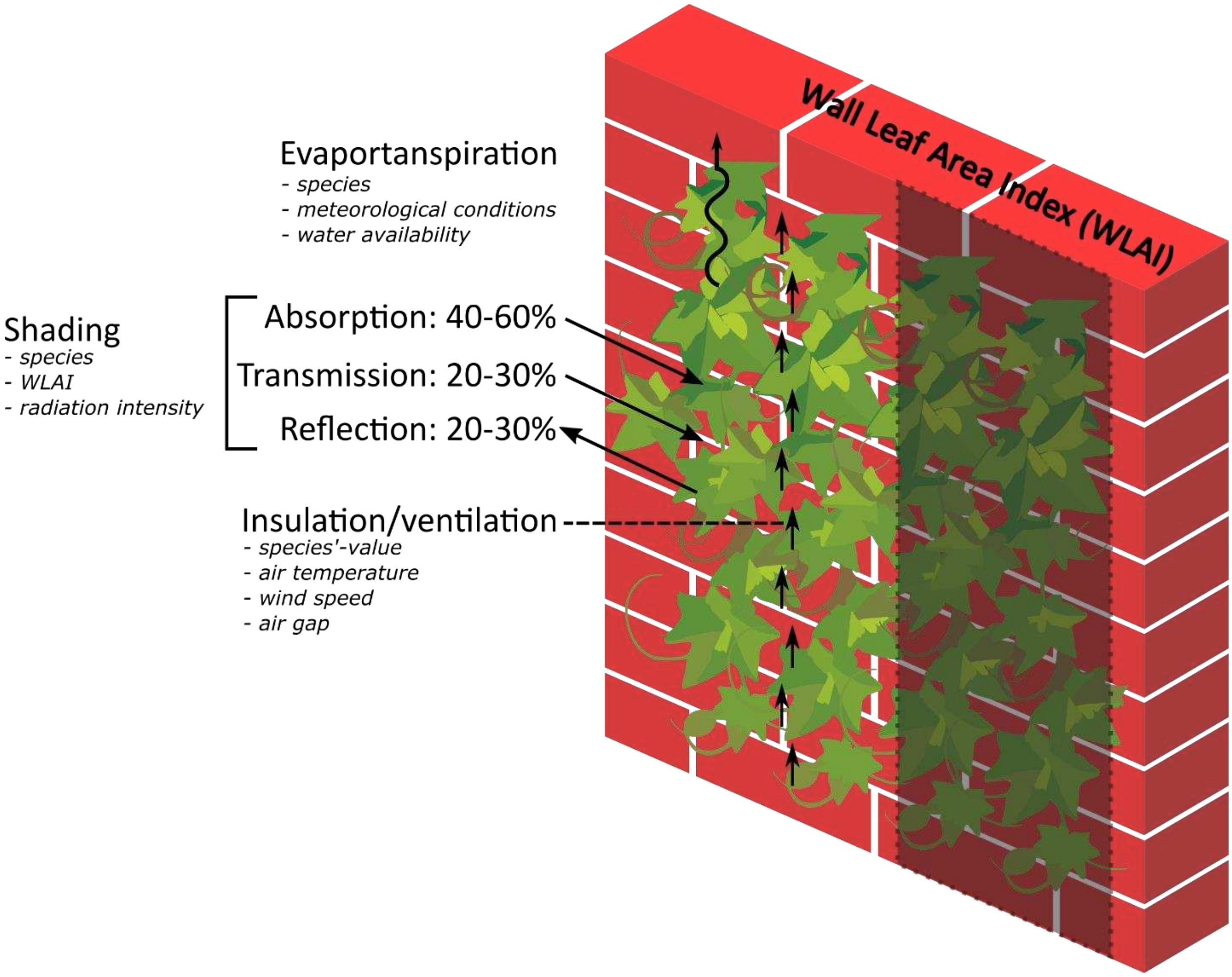


Figure 4: Schematic overview of cooling mechanisms and their determining parameters. It also shows the correct use of the term Wall Leaf Area Index (WLAI) when studying green walls, which is the amount of vegetation surface area per vertical wall surface area [m^2 m^{-2}].

2.1.1 Shading

Shading is a very important cooling mechanism of GW and it is often considered the most important factor for cooling by vegetation (Pérez et al. 2011b; Yin et al. 2017). For example, it can reduce cooling costs in warm climates by up to 61% (McPherson, Herrington and Heisler, 1988). Shading of vegetation prevents the underlying surfaces from warming up and overheating (McPherson et al. 1988; Wong et al. 2009) by the absorption (and reflection) of a certain fraction of solar radiation by the plants, so incoming radiation does not reach the building wall. It is estimated that the global absorption coefficient of a GW (accounting for the coverage of the wall by leaves) is about one third of that of a typical wall (Kontoleon & Eumorfopoulou 2010; Perini et al. 2011). The amount of transmitted solar radiation for one leaf layer is about 45% of the incident radiation and lowers to 31%, 27%, 22% and 12% with increasing layers up to five for *Parthenocissus quinquefolia* (Ip, Lam and Miller, 2010). However, the shading potential of vegetation is greatly dependent on the plant species and environmental parameters. Another fraction of the incoming radiation is reflected by the leaves, depending on their albedo. The remaining solar radiation is transmitted. Reflection and transmission account both for about 20-30% of the incoming radiation. The contribution of each of these three processes is mostly determined by the leaf pigments (which determine the leaf colour) and thickness (Jones, 1992).

In contrast to the above, shading by vegetation can also result in a need to increase energy consumption up to 28% for heating in winter or in cooler climates (< 20°C) (McPherson, Herrington and Heisler, 1988). This means that the designer must carefully consider the local climate in order to integrate the right green infrastructure. Deciduous plants will obviously retain more radiation in the summer than in the winter. In this way shedding can be used as an advantage, so that a self-adjusting shading system is developed (Stec, Van Paassen and Maziarz, 2005), which gives the benefit of shading in summer and transmission of solar heat in winter. Of course woody structures remain during winter, but their effect on shading is less compared to plant leaves.

The effect of shading is related to the radiation intensity (Mazzali *et al.*, 2013), which depends on the solar angle, cloudiness and sky clearness. For example, Perini *et al.* (2011) performed an experiment in the Netherlands in autumn with no direct sunlight and measured only a small difference in outside wall surface temperature of 1.2°C, 2.7°C and 5°C between a bare wall and (i) a dGF, (ii) an idGF and (iii) a LWS, respectively. In contrast, in a summer situation in Germany, Hoelscher *et al.* (2016) have found an outside wall temperature reduction of 10.5°C for an idGF compared to a bare wall.

Furthermore, shading also depends on the Leaf Area Index (LAI) (Ip, Lam and Miller, 2010). Mostly, LAI is defined as the amount of vegetation surface area per ground surface area [m^2 m^{-2}] (Jonckheere *et al.*, 2004). In the case of vertical greening this definition of LAI is less relevant, as the substrate of interest (the wall) is vertically oriented. Therefore, to avoid confusion, we propose the consistent use of the wall-projected leaf area, namely the Wall Leaf Area Index (Cameron, Taylor and Emmett, 2014) when describing the effect of leaf area on walls (Figure 4). Although the term WLAI is rarely used in the literature considering green walls, the reported LAI actually refers to WLAI. The modelling study by Wong *et al.* (2009) showed that the shading coefficient (this is the ratio of the solar radiation reaching the wall covered with plants by transmission, to the solar radiation reaching a bare wall) decreases linearly with WLAI (Figure 5). The figure shows that the shading coefficient decreases by 30% when WLAI doubles.

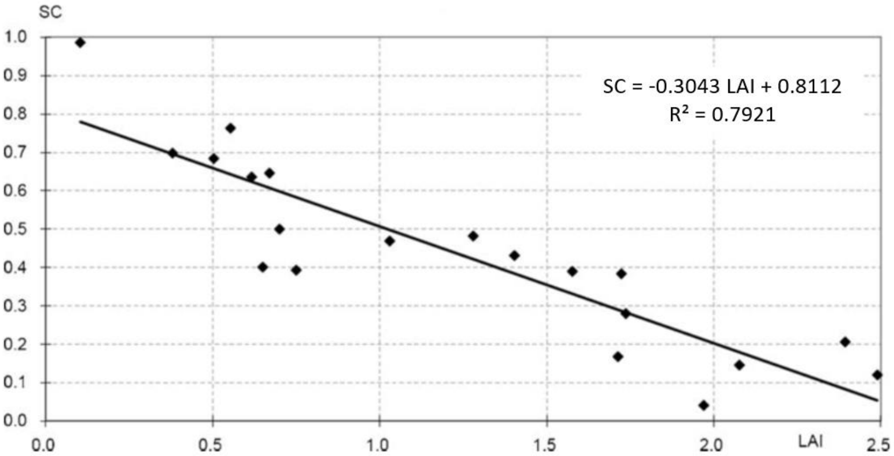


Figure 5: Correlation equation between shading coefficient (SC) (the ratio of the solar radiation reaching the wall covered with plants by transmission, to solar radiation reaching a bare wall) and wall leaf area index (WLAI/LAI). Each point represents a value of WLAI (x-axis) and SC (y-axis) for a certain green wall species. A linear trend line is plotted through them, of which the equation is given in the figure (Wong et al. 2009).

2.1.2 Evapotranspiration

Evapotranspiration consists of two separate processes: evaporation and transpiration. During transpiration, water is released by living plants as a result of opening the stomata for CO_2 uptake, necessary to drive the photosynthesis process. Transpiration results in cooling of the air surrounding the leaf. According to Stec *et al.* (2005), about 60% of the accumulated energy in a leaf can be released by transpiration. The transpiration rate process depends on plant species, WLAI, meteorological conditions (like air temperature, air humidity and wind speed) and soil/substrate water availability. Only unstressed plants (e.g. well-watered) have high transpiration rates (Cheng et al. 2010), because the stomata are only fully opened in optimal environmental conditions (hereby neglecting any adverse pathogenic effect). This underlines the importance of adequate irrigation, not only for the LWS, but also for soil-based vegetation, to obtain optimal cooling by transpiration (Hoelscher *et al.*, 2016). Evaporation, on the other hand, accounts for the transfer of water to the air from the soil or from water intercepted by the plant during precipitation or dew. In LWS, water can also evaporate directly from the substrate material, which results in additional cooling of the underlying wall, apart from the plants themselves. Differences in evaporation from LWS substrates were described in detail by Malys *et al.* (2014). Because LWS can cool due to both transpiration and evaporation, they have greater cooling potential than other types of green walls (Ottelé *et al.*, 2011).

In general, evapotranspiration has a smaller impact on cooling than shading, but it has a greater significance in lowering ambient air temperature on a larger local scale, as demonstrated by Huang *et al.* (1987). The effect of evapotranspiration on the surrounding climate is often considered irrelevant in field studies. This is mainly because the size of the green wall is often too small to have a measurable impact on the local microclimate. For example, Perini *et al.* (2011) reported no temperature differences up to 10 cm in the vicinity of GW. Djedjig *et al.* (2013) reported an increase in relative humidity of 6-8% in in a scale model of a street canyon with dimensions of 5.0 x 1.3 x 1.1 m. However, it should be noted that in this latter study one of the two façade walls of the street canyon was entirely greened, which is mostly not a representative situation in reality. Daemei *et al.* (2018) is one of the few studies that considers outdoor air temperature at several distances from the GW (0, 0.5, 1 and 2 m). These were measured on a real wall in Tehran (Iran). These authors suggested a decrease in air temperature in a street canyon of 0.8°C. This result should, however, be considered with some caution, since important parameters such as wind speed and direction have been omitted in this study.

2.1.3 Insulation and ventilation

Insulation through a GW is caused by stagnant layers of air in the cavities between leaves. This causes a reduction in extremes of surface and air temperature in both summer and winter, but is considered the most important in winter or in a cold climate, as it acts as a protection against freezing (Ottelé et al. 2011; Sternberg et al. 2011; Carlos 2015; Djedjig et al. 2017; Serra et al. 2017). It has been shown that different types of plant species make wind flow pass in different ways (Koch, Samson and Denys, 2019), which further complicates the insulation or ventilation capacity of green walls. Furthermore, the LWS substrate offers additional protection for the building under extreme climate conditions. Insulation of LWS is partly dependent on the properties of the substrate (Ottelé and Perini, 2017). Because of this substrate, LWS have, according to Ottelé *et al.* (2011), better insulation properties than other types of green walls. In contrast, Tudiwer and Korjenic (2017) found for a winter situation, better insulation properties for and idGF than for a LWS, as the wall behind their idGF was 3.5°C warmer than the bare wall, compared to a LWS that was only 0.5°C warmer than the corresponding bare wall. In combination, in idGF's or some LWS types, the layer of air between the plant material and the wall, defined as the air cavity, can also act as a stagnant air layer, which then acts as an insulation barrier. In general, the insulation properties of a material are expressed in U-, R- or λ- values. These parameters are related by the following expression:

$$U = \frac{1}{R} = \frac{\lambda}{d} = \frac{q}{\Delta T} \quad (1)$$

with U the heat transfer coefficient [W m^{-2} K^{-1}], R the heat resistance coefficient [m^{2} K W^{-1}], λ the thermal conductivity [W K^{-1} m^{-1}], d the thickness of the vegetation [m], q the heat flux [W m^{-2}] and ΔT the temperature difference over the vegetation layer [K]. Table 1 (additional information) shows an overview of papers that have reported R values (or others, that can be converted to R values). To illustrate, and to compare, additional R-values of commonly used building materials are provided. As is the case for shading, it is observed that solar radiation is a determining factor and that the heat transfer coefficient is larger in summer than in winter. In addition, LWS isolate more than dGF, and are comparable or even better than commonly used building materials.

Furthermore, several authors emphasize the obstruction of convective heat transfer, in warm climates or in the summer season, from the building walls to the environment at night, due to insulation by plant covering (Eumorfopoulou & Kontoleon 2009; Mazzali et al. 2013; Koyama et al. 2013). This results in covered walls staying warm even longer during night than bare walls, which is undesirable for human comfort.

In summer or in hot climates, *ventilation* can facilitate convective cooling (Hoyano 1988; Haggag et al. 2014). This can be achieved by actively blowing air through the vegetation or by designing the system so that air flow is facilitated (Davis and Hirmer, 2015). In other words, a correct design is needed depending on the type of climate. The study of Perini *et al.* (2011) found that the wind speed fell to almost zero in the foliage of dGF compared to the wind speed 10 cm in front of it. Susorova *et al.* (2014) also found wind speed reductions of up to 43% on west-oriented walls, which indicates insulation properties. The findings above suggest that different GW-systems can be used according to their purpose; either insulation (dGF and LWS) or ventilation (idGF).

2.2 Meta-analysis

The following sections provide an overview of the articles reviewed in a table per type of green wall (direct, indirect and living wall system) (see additional information). A separate section provides an overview of studies that use numerical models. An article can appear multiple times if different systems are considered and if a double approach (both experiment and modelling) is used. The thermal effect is expressed in various ways in the literature: these are listed in **Error! Reference source not found.**2 (additional information), along with the abbreviations used in this review. In a subsequent chapter we aim to normalize these data to perform a meta-analysis.

2.2.1 Variables of importance

The comparison between systems in terms of cooling properties is often challenging, due to the structural diversity of green walls, as both plant material and substrate (both for GF and LWS) are responsible for thermal effects. Furthermore, the mechanical structure of the suspension system and the soil properties of rooting substrates are often not sufficiently discussed. Besides, many companies are not willing to share their technologies which makes an adequate assessment of the systems difficult. In this review, a distinction was made between the different green wall types because of their functional differences, and four categories were distinguished: direct green façade (dGF), indirect green façade (idGF), living wall system (LWS) and modelling studies.

Furthermore, climatic differences can make comparisons between studies difficult. Therefore, we have included the Köppen climate (Peel, Finlayson and McMahon, 2007), season and orientation in our meta-analysis. Also differences in meteorology (Jim, 2015), orientation (Kontoleon & Eumorfopoulou 2010; Pérez et al 2011a; Carlos 2015; Jim 2015) and water availability of the plants (Ottelé *et al.*, 2011) make comparison a challenge. The uncontrollable factors, at least in field studies, such as wind speed, amount of solar radiation, air temperature and relative air humidity make it almost impossible to compare different studies. To reduce these variations between experiments, different types of green walls should be tested in a 'common garden' experiment like the one by Wong *et al.* (2010).

Another important variable is the WLAI, which is a good benchmark and higher WLAI mostly leads to better cooling performance (Pérez et al. 2017). However, WLAI is not static within a species and, for example for deciduous species, changes over season. Nevertheless, despite of its importance, values of WLAI are often not considered in studies. Also the foliage thickness can be considered of great importance (Coma *et al.*, 2017).

Some research papers did not report the plant species investigated (Stec et al. 2005; Alexandri & Jones 2008; Wong et al. 2010; Chen et al. 2013; Haggag et al. 2014; Tudiwer & Korjenic 2017; and others), especially in LWS experiments and modelling studies. It is essential to know the growth requirements of the plant species in their environment to prevent diminished cooling performance or growth failures (Pérez et al. 2011), e.g. due to drought of the substrate. Furthermore, plant physiology, morphology, phenology and sensitivity to pests all contribute to one or more of these cooling mechanisms (Cameron, Taylor and Emmett, 2014).

Finally, most articles focused on changes in the outside wall temperature and indoor temperature caused by green walls compared to a bare wall, while there are not many studies on changes in the local microclimate, which is important in relation to the urban heat island effect. Similarly, no study exists where all four temperature regions are assessed and compared, namely the indoor ambient temperature, inside wall temperature, outside wall temperature and outdoor ambient temperature. Also, only a few studies quantified potential reductions in the energy cooling load and these are mostly modelling approaches (Stec et al. 2005; Alexandri & Jones 2008; Kontoleon & Eumorfopoulou 2010; Carlos 2015; Djedjig et al. 2016; and others). To summarize, it can be said that every single system has its own unique impact on heat mitigation and therefore making predictions is a challenge.

2.2.2 Overview of field studies

2.2.2a Direct green façades

Hoyano (1998) was the first to perform pioneering work on the cooling capacities of climbing plants. In Fukuoka, Japan, they found that ivy (*Hedera*) or *Parthenocissus* coverage could decrease the outer wall temperature up to 13°C, which resulted in a decrease in indoor temperature of about 7°C in the summer for an outdoor temperature up to 35°C. Likewise, Susorova *et al.* (2014) found an average reduction in wall temperature of 0.7°C up to a maximum of 12.6°C on an east-oriented façade in summer in Chicago, USA. Eumorfopoulou & Kontoleon (2009) found a maximum reduction of outside wall temperature of 8.3°C and an average of 5.7°C, on a multi-story building partly covered with *Parthenocissus* for the summer in Greece. For interior wall temperature, a maximum reduction of 1.6°C and an average of 0.9°C was observed. In general, it was shown that the differences between minimum and maximum temperatures of a vegetated wall were lower than those of a bare wall, indicating that plants absorb and reflect a great amount of solar radiation. On the other hand, for the winter season, Sternberg *et al.* (2011) and Bolton *et al.* (2014) (United Kingdom) found a moderating effect of ivy on the outer wall temperature (3°C and 0.5°C higher, respectively). In contrast to summer situations, the walls benefit less sun exposure during a winter day, which prevents the wall from heating up. However, in the study of Sternberg et al. (2011), the insulation effect predominated in the winter.

Cameron *et al.* (2014) investigated a range of dGF species and pointed out that not all plant species perform equally well in terms of the degree and mechanism of cooling. They found that walls covered with *Prunus laurocerasus* were up to 6.3°C cooler on the outer surface than bare walls and their surrounding temperature (80 mm distance) was about 3°C lower than the ambient outdoor temperature. Also, dead *Prunus* individuals, that had been excised to inhibit transpiration, showed a significant lower outer wall temperature than bare walls, but a higher temperature than walls covered with living plants. Cameron *et al.* (2014) also tested five plant species (Figure 6) in a growth chamber, half of the replicates being entirely sealed with poly 1-acetyloxiethylene to prevent transpiration. In general, they found that all species significantly reduced the wall temperature, whether or not they were excised or sealed, underlining the importance of the shading effect. Interestingly, species seemed to differ in their cooling mechanisms. The values for average reduction of wall temperature per species were normalised for WLAI. In the case of *Hedera*, *Lonicera* and *Jasminum*, shading was the most important factor. In contrast, cooling from *Fuchsia* was twice as high for evapotranspiration than for shading. For *Prunus* and *Stachys*, both mechanisms were approximately equal. Temperature values are shown in Table 3 (additional information). The authors suggested *Hedera* and *Stachys* as the best candidates – of the considered species - for wall cooling. This effect of merely shading has also been investigated by Hoelscher *et al.* (2016). By dehydrating the plants, they found that shading was the most important cooling mechanism, in agreement with the study of Cameron *et al.* (2014).

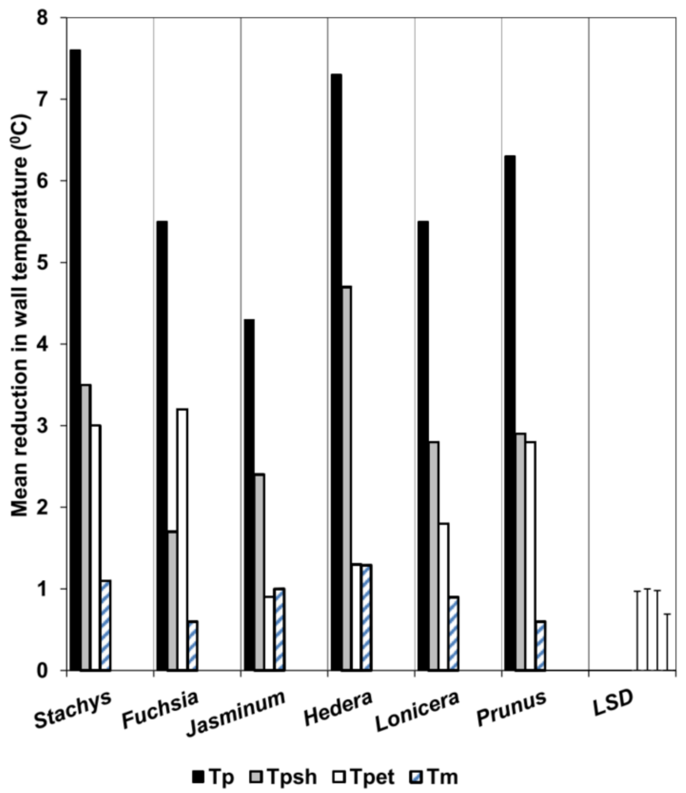


Figure 6: Comparison of mean absolute cooling (°C) for plant species (Tp), shade (Tpsh), transpiration (Tpet) and evaporation from medium (Tm). Bars = Least Significant Difference (LSD) (P = 0.05) respectively; d.f. = 32, for aforementioned parameters in order from left to right (Cameron et al. 2014).

2.2.2b Indirect green façades

Pérez *et al.* (2011 a&b) studied a double skin green façade (*Wisteria sinensis*) made of modular trellis in Spain, with an air space between 0.8 m and 1.5 m between the structure and the green façade. On average, outer surface temperatures on covered walls were 5.5°C lower than uncovered walls. Maximum temperature differences can reach up to 15.2°C in summer (September) with a monthly averaged air temperature of 20.7°C. Another experiment performed in Spain in summer (Coma *et al.*, 2014) showed a similar decrease in wall temperature of 14°C, while researchers from Slovenia (Šuklje et al. 2016) found a decrease up to 34°C. Not many studies have examined the influence of cavity depth (the distance between the green wall and the building wall). Lee & Jim (2017) compared different cavity depths and concluded that an air gap of 1 m could enhance ventilation more effectively compared to a gap of 0.3 m.

Another case study by Pérez *et al.* (2017) in Spain - a double skin green façade with *Parthenocissus tricuspidata* covering the east, south and west orientations of a cubicle - was performed to investigate the influence of the building façade orientation on the shading effect. Reductions of 15.0, 16.0 and 16.4 °C for the east, south and west orientation, respectively, were observed at different times of the day following the sun's hemispherical path. Similar results were found in the study of Coma *et al.* (2017) in Spain. Jim (2015) recorded the highest cooling rates for south and east oriented walls, in Hong Kong, China, which were also under the greatest solar radiation exposure. This is in agreement with Koyama *et al.* (2013), who showed that solar radiation exposure was one of the main determinants of cooling capacity.

Morphological and physiological plant traits responsible for the differences in cooling capacity between species were identified by Koyama *et al.* (2013) for a summer situation in Japan. The species considered and their respective temperature reductions of the underlying walls are shown in Table 4 (additional information). Furthermore, they found that, in addition to other morphological parameters, the coverage percentage was one of the main determinants of the wall surface temperature: the higher the coverage, the lower the wall temperature, in agreement with Pérez *et al.* (2017). In the latter study, the WLAI, which is a key parameter determining foliage density, had a value between 3.5 and 4.

Koyama *et al.* (2015) investigated the various cooling mechanisms of green walls. However, to stop transpiration, Koyama *et al.* cut off the stems of all plants from one of the GWs, instead of sealing them as was done by Cameron *et al.* (2014) for dGF, after which the transpiration rate decreased sharply. The transpiration cooling effect in itself led to a small decrease of the inner wall temperature and room temperature of both 0.2°C. In contrast, the shading effect was much greater with a temperature reduction of 8.6°C and 4.0°C for the inner wall temperature and room temperature, respectively. Similar reductions in indoor air temperature were found by Ip *et al.* (2010). Overall, they found that experimental interior temperatures dropped by 4 to 6°C compared to no treatment.

A study of Schettini *et al.* (2016) confirmed the abovementioned thermal effects of idGF's on the outer wall temperatures in winter, i.e. a small reduction in the maximum wall temperature and an increase in the minimum wall temperature since vegetation acts as an additional thermal insulation. A similar reduction was found by Wong *et al.* (2010), where the bare outdoor wall temperature was 4.4°C lower in winter than a covered wall. In general, the insulation effect of idGF in winter is limited because of the air gap that facilitates ventilation.

2.2.2c Living wall systems

Because of the large number and variety of studies considering LWS, this section is divided according to the parameters that determine local cooling effects.

(i) Substrate

LWS differ from previously discussed soil-bound systems in terms of their rooting substrate. Regarding evapotranspiration, shading and insulation, LWS substrates have their own characteristics, such as moisture content and thermal conductivity of the substrate, which are often not considered separately in literature, which complicates the parameterisation of plant characteristics. Substrate properties contribute substantially to the energy performance of the LWS, but often these substrates are not sufficiently described to assess their performance. Few studies made direct comparisons between LWS and other types of green walls. Wong *et al. (2010)* compared different systems of LWS and one green façade. The best thermal performance was shown for a LWS with plant panels consisting of steel mesh frames and a LWS with peat moss substrate in a steel cage, with a maximum reduction of the outer wall surface temperature compared with a bare wall of 11.6°C and 10.9°C, respectively, at noon in spring in Singapore. Of all types, the green façade performed the least, with a maximum reduction in wall surface temperature of 4.4°C in June. This could be explained by the fact that the substrate layer of the LWS acts both as an insulator and a cooler through evaporation. These results are in agreement with the study of Coma *et al.* (2017), who also found a better energy performance for LWS in summer than for GF.

Cheng *et al.* (2010) used grasses in their experiment and investigated the temperature of the substrate (Hong Kong, China). They found that the substrate was on average 1°C cooler than the ambient air, but the difference could be as high as 14°C. At night the substrate was about 2°C warmer than the surrounding air. Regarding substrates, Charoenkit and Yiemwattana (2016) (Thailand) found that LWS with a continuous substrate (this means a non-modular system), like felt, have less cooling performance compared to modular systems, which is in agreement with the findings of Wong *et al.* (2010) and Mazzali *et al.* (2013). Mazzali *et al.* examined three LWS in different regions of Italy, of which felt systems performed better than planting pots filled with soil.

(ii) Plant morphology

Interestingly, according to Bianco *et al.* (2017) (Italy), different substrate types cause differences in WLAI. They performed a one year measuring campaign on test modules with two different plant species and two different substrates. The different substrate types resulted in different WLAI ranging from 1.4 to 2.0 for *L. nitida* and from 4.6 to 4.7 for *B. cordifolia*. Furthermore, the influence of leaf size on the cooling effect of LWS was studied by Charoenkit & Yiemwattana (2017) for three species with different leaf size. The cooling capacity among these plants was significantly different. *Cuphea hyssopifola*, which had the smallest leaves and the highest WLAI, turned out to have the best wall surface temperature reduction performance, whereas *Excoecaria cochinchinensis* showed the least surface temperature reduction, although it had a larger WLAI than *Tibouchina urvilleana*. According to the authors, this demonstrates that in addition to WLAI, leaf size is an important parameter that influences the thermal performance of plants. In this case, smaller leaves have more cooling capacity. Although larger leaves are associated with a larger shading effect, they have a thicker boundary layer limiting heat dissipation by convection. Nevertheless, these differences in cooling capacity could also be due to other factors as different transpiration rates between species. Further studies should clarify the function of leaf size and focus on more plant species with different leaf sizes to increase empirical evidence of smaller leaves performing better in terms of cooling.

(iii) Summer-winter differences

Coma *et al.* (2017) studied an indirect green façade with deciduous species and a living wall system with evergreens, both in summer and winter, in Spain. For summer conditions Coma *et al.* (2017) found better energy savings for the LWS than for the idGF. In winter, no effect of the idGF on energy savings could be found, but the LWS provided energy savings of up to 4.2%. Winter studies are still scarce, but were done by e.g. Bianco *et al.* (2017) and Tudiwer and Korjenic (2017). Bianco *et al.* (2017) (Italy) found that during winter, the green wall reduced heat losses up to 63% and 70% compared to a bare wall for *L. nitida* and *B. cordifolia*, respectively. Djedjig *et al.* (2017) in France also emphasized the effect of LWS on buildings in a reduced scale street canyon experiment both in summer and winter. In summer the wall temperature behind the LWS was 15°C lower and indoors it was 5°C cooler than the bare wall situation. In addition, they found a 97% reduction in heat gain, mainly caused by shading and evapotranspiration. In contrast, due to insulation effects, heat loss reduction in winter was up to 80%. Similarly, Medl *et al.* (2017) reported that the maximum wall surface temperature covered by a LWS on a hot summer day in Austria was 18.9°C lower compared to a bare wall.

(v) Cavity temperature

Perini *et al.* (2017) focused on the air temperature in the cavity between vegetation and wall, since this air can be used as fresh supply air in air conditioning systems. The air in the cavity had a temperature that was on average 5.2°C lower in June and July compared to the outdoor air temperature, resulting in a 26% reduced energy consumption to maintain the indoor air temperature at 26°C. In other words, the air cavity created an additional thermal insulation layer, as confirmed by Bianco *et al.* (2017). Also, Chen *et al.* (2013) found that the air layer between the wall and the LWS showed a maximum temperature reduction of 9.7°C compared to a bare wall and an average reduction of 3.1°C.

(vi) Time delay

Many studies report a delay in the daily temperature fluctuation in LWS compared to bare walls. Cheng *et al.* (2010) found that vertical green caused a delay of about 4 hours in the heat transfer, which means that the temperature fluctuation of the wall can be buffered by vegetation. Likewise, Chen *et al.* (2013) focused on the microclimate between the building wall and the LWS. They found that the amplitude of the daily temperature fluctuation was much smaller in the vegetated wall compared to the bare wall. Moreover, the outer wall surface of the LWS was a maximum of 20.8°C cooler than the bare wall and the indoor wall was a maximum of 7.7°C cooler. At night, the air layer remained slightly 2 degrees warmer than the ambient air. Vegetation therefore keeps the wall warm at night, but if a wall warms up less during the day, this logically makes it release less heat during the night. The time delay effect can also be seen in Figure 7.

2.2.3 Modelling studies

In general, few modelling studies have been performed on GW. Nevertheless, models can often be used to extend the limited knowledge from experiments to broader applications and to experiment virtually, e.g. with different amounts of green wall surface and different climate zones. It should be noted that the modelling studies in the literature often lack important information to compare the outcome with each other. First, validation of models is often lacking which adds an uncertainty to these studies. Secondly, the studies often did not specify what type of green wall or even which plant species was/were considered in the models. At last, these studies fail to consider all three cooling effects discussed above, except for Davis et al. (2015) and Djedjig *et al.* (2016). Therefore, this section is divided according to the cooling mechanisms covered by the corresponding studies. Furthermore, several other important model parameters are discussed.

(i) Effects of evapotranspiration

For example, the study of Stec *et al.* (2005) only looked at the evapotranspiration effect of vegetation, without considering shading and/or insulation. In their study, they created a mathematical model based on the Pennman-Monteith approach (Montheith, 1981) to simulate heat exchange between the layers of a double skin green façade. The experimental setup considered five layers: a glass screen, an external air cavity, a climbing plant, an internal air cavity and a wall. The plants are replaced by sun blinds for comparison. The thermal performance of the materials was derived from experiments and the temperature output from the model was compared with the experimental output. They found that the temperature of the plants never exceeded 35°C, while the sun blinds could reach over 55°C. Internal wall temperature difference was on average 3.8°C. Furthermore, they found that the energy consumption for cooling decreased by 19%.

(ii) Effects of shading

On the other hand, Alexandri and Jones (2008) only took the shading effect into account. They developed a two-dimensional CFD model where 9 cities in 9 different climate types (from tropical to sub-arctic) were considered on a typical day in the hottest month. Four types of vegetation covering were assessed: no green, green roofs, green walls and both green roofs and green walls. Green walls and roofs covered 100% of the available surface area. These simulations were executed for three different canyon geometries (aspect ratio's L/H 5/10 m, 10/5 m and 15/5 m), two orientations (E-W and N-S) and two wind flow directions (perpendicular and parallel to the street canyon). They found a significant improvement in thermal comfort especially, in hot climates. Furthermore, green walls seemed to perform better than green roofs in street canyons for all climate types. Also, the cooling effect of green walls was weaker in wider street canyons. Canyon orientation and wind direction seemed to have little effect on the performance of green walls. It must be noted that this study was not validated with experimental data, nor were the green wall system and the plant species specified.

(iii) Effects of shading and evapotranspiration

Kontoleon and Eumorfopoulou (2010) investigated both shading and evapotranspiration effects. They used a thermal network model to investigate the influence of orientation and covering percentage of green walls. They considered different types of building insulation, which is rare in most other studies. They found outer wall surface temperature differences between plant-covered and bare walls of on average 10.8°C up to 19.3°C for the west-oriented wall at daytime. At night, differences were smaller, on average 1.9°C reaching up to 2.4°C. The authors' findings suggest a great impact of the shading effect, where vegetation absorbs a lot of the solar energy. Regarding the covering percentage (0 to 100%), a higher covering percentage seems to perform better in terms of cooling, with the best results on the east and west side of the building. Finally, energy cooling load reduction was found to be 20.1% for west sided walls. Similarly, Susorova *et al.* (2013) proposed a mathematical model of a green façade (*P. triscuspidata*), taking into account weather conditions, climatic zone, wall orientation, wall assembly and plant species' characteristics. The latter, includes leaf absorptivity, leaf width, WLAI, radiation attenuation coefficient (i.e. the decrease in absorbed radiation through the plant canopy, between 0 and 1) and stomatal conductance, is lacking in many modelling studies, but was the focus in this research. The model was validated with a case study of a dGF of *P. triscuspidata*. The simulations showed a reduction in outer wall surface temperature varying from 12.3 to 13.8°C. WLAI and radiation attenuation coefficient seemed to be the most important parameters and both should be high to achieve the best cooling results. The most effective meteorological variables were, in order of importance, solar radiation, wind speed, relative air humidity and air temperature.

(iv) Effects of shading, evapotranspiration and insulation

Davis *et al.* (2015) are one of the few authors who considered all three cooling mechanisms, also using a model based on the Pennman-Monteith approach. Another study in which the three cooling mechanisms were considered, was performed by Djedjig *et al.* (2016), who validated a thermo-hydric model with experimental data from (Djedjig, Bozonnet and Belarbi, 2013) before applying it to a model case study, for two climates, France and Greece. For both climate zones the latter authors found a decrease in both heating (winter) and cooling (summer) energy use. Regarding orientation, they found the best results for south and west oriented walls (Figure 7) for summer. Nevertheless, a clear difference in energy use was also seen for the other orientations. Figure 13 clearly shows the mitigating effect of the considered green wall on the covered wall (Djedjig *et al.* 2015). Not only are the amplitudes of the graphs smoothened for the covered walls compared to the bare walls; also a clear time lag can be seen, which was discussed earlier. This means that greened walls not only inhibit heating or cooling of the walls, they also cause the underlying wall to gain and lose heat at a later time in the day. Djedjig *et al.* (2016) expanded their model for a street canyon case. They found cooling load reductions up to 37% for the Greek case.

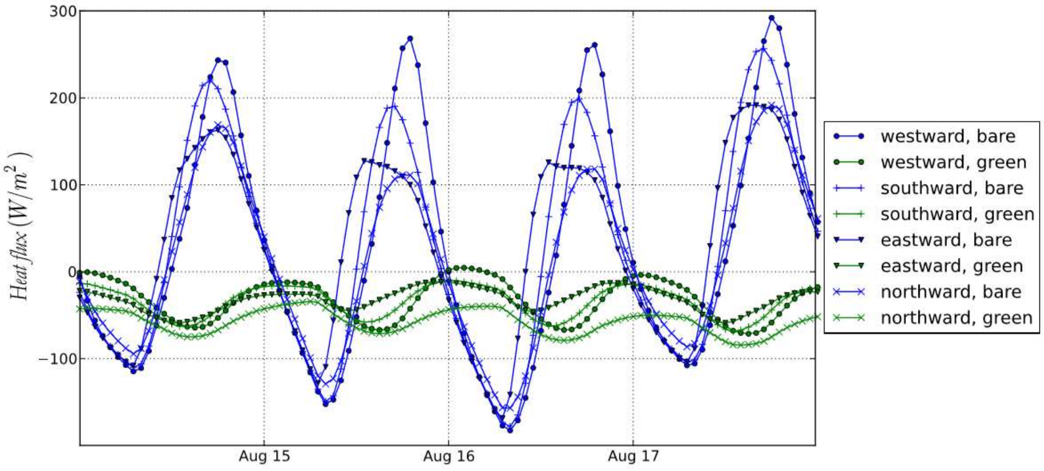


Figure 7: Comparison of transmitted heat flux to the building located in La Rochelle (France) through bare or vegetated facades according to various wall orientations (Djedjig et al. 2015).

(v) Vegetation layer thickness

Considering the thickness of the vegetation layer, Holm (1989) was one of the first authors to assess the thermal capacities of green building coverings. He designed a dynamic computer model that was later validated with experimental data. Earlier experiments have shown that foliage thickness of climbers from 20 cm onwards did not cause any additional changes in shading. Therefore, a thickness of 20 cm was used in the model. Furthermore, the author found that the thicker the vegetation layer, the less important the morphology of the plant species in the overall cooling capacity. This was, however, contradicted by several other authors (Wong et al. 2009; Kontoleon & Eumorfopoulou 2010). Wong *et al.* (2009) performed a modelling study to look at the indoor temperature and the decrease in energy consumption by considering green walls in a tropical climate. Climate conditions were from real weather data and vegetation parameters were taken from a field study, also used in Wong *et al.* (2010). These authors found that shading coefficient and WLAI are strongly correlated (see Figure 5).

(vi) Thermal transfer/resistance and heat flux

Interestingly, some simulation studies rendered U, R or λ values for green walls. For example, Larsen *et al.* (2014) modelled an indirect green façade (double skin). They adopted the model of Stec *et al.* (2005), which was originally meant to study the thermal effects of green roofs. The calculated thermal resistance coefficient of the green wall was around 0.15 m^2 K W^{-1}, which is in accordance with Perini *et al.* (2011) (experiment on direct green façade, R = 0.09 m^2 K W^{-1}). Šuklje *et al.* (2016) modelled an indirect green façade and found heat fluxes of 41.2 W m^{-2} for a wall with a thermal resistance of 0.6 m^2 K W^{-1} (non-insulated), 12.2 W m^{-2} for a thermal resistance of 2.1 m^2 K W^{-1} (moderately insulated) and a heat flux of 5 W m^{-2} for the highest thermal resistance of 5.3 m^2 K W^{-1} (low energy building). Regarding insulation materials, Olivieri *et al.* (2017) developed a model to estimate the threshold value for wall insulation behind a LWS. They found a non-significant increase of wall temperature if polystyrene (λ = 0.035 W m^{-1} K^{-1}) insulation was thicker than 90 mm, for summer conditions in Spain. This is the only study that directly linked vegetation with insulation material thickness. This is in accordance with Bevacqua *et al.* (2018), who found that the best performance of LWS occurs when it is installed on a non-insulated wall. When the insulation thickness increases, the LWS becomes less functional in terms of cooling. It must be noted that this latter modelling study has not been validated.

3 Synthesis

3.1 Meta-analysis

This literature study has shown that green walls can reduce temperature extremes, both in warm and cold situations. Figure 8 shows a meta-analysis of the temperature difference between bare and green walls in summer (left panel) and in winter (right panel). For summer situations it is clear that modelling studies overestimate the cooling effect of green walls by about 5 degrees Celsius. On the other hand, experimental studies show a good agreement between the different types, with LWS providing a slightly larger cooling effect. No thermal modelling studies have yet been performed for winter conditions. Certain studies report energy saving percentages in terms of cooling or heating capacities of green walls (Figure 9). All other reports provided different types of output, such as ambient air temperature, indoor air temperature, and indoor wall temperature. For these outputs, there were not enough papers available to provide a meta-analysis. This indicates that there is a strong need for a uniform model output to quantitatively assess the effects of different types of green walls in order to make comparisons between studies possible and to make a scientifically well-founded choice for the best green wall system in a specific environment.

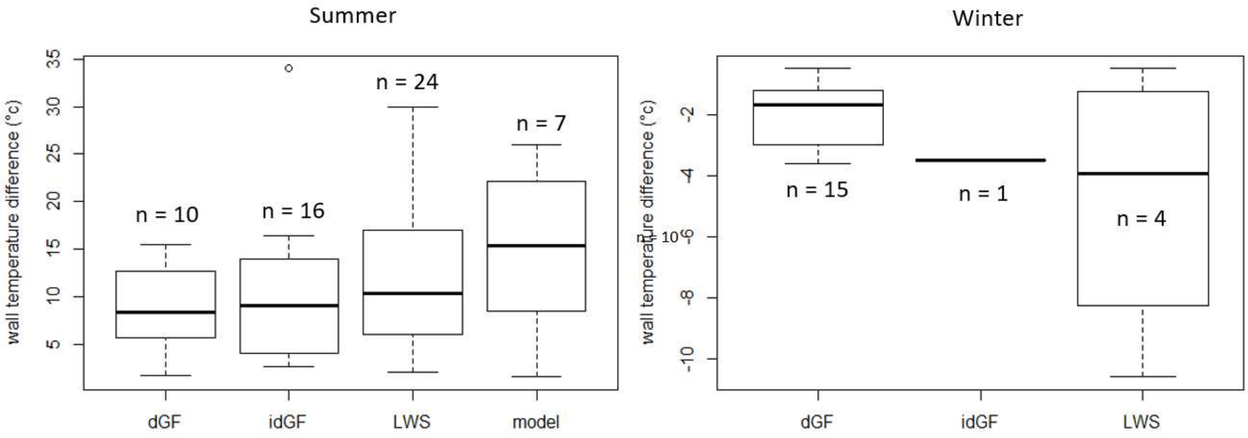


Figure 8: Outdoor wall temperature difference (°C) between bare and green walls (bare wall temperature – covered wall temperature). In summer (left panel), greened walls are cooler than bare walls. In winter (right panel), greened walls are warmer. N = number of studies considered. dGF = direct green façade, idGF = indirect green façade, LWS = living wall system, model = modelling studies. For both summer and winter, no statistically significant differences were found.

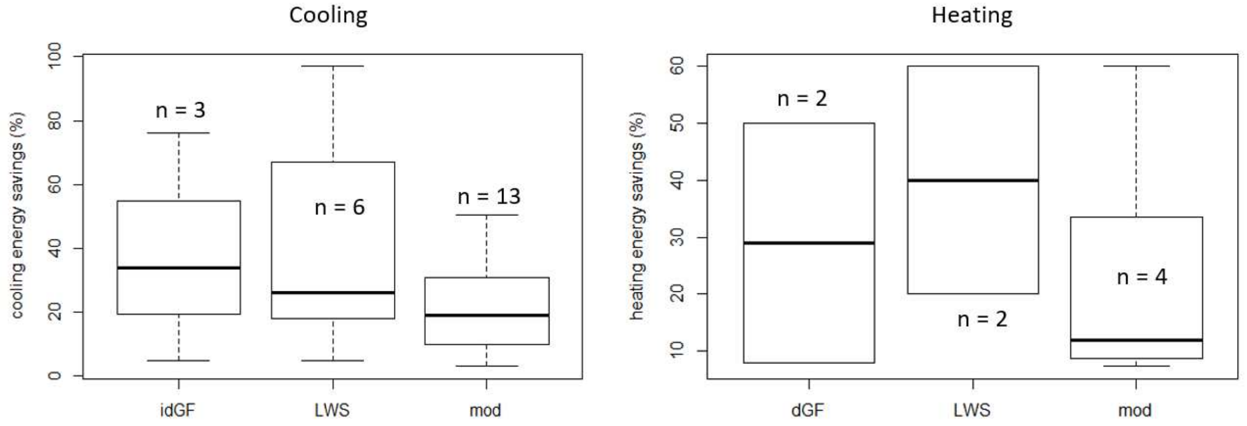
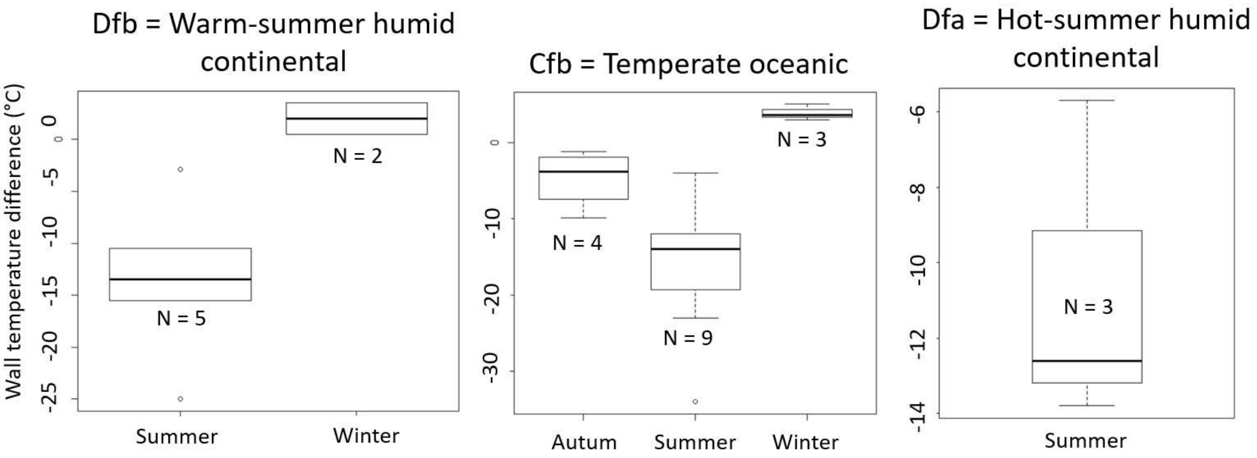


Figure 9: Energy savings (%) compared to no greening for cooling (left panel) and heating (right panel). N = number of studies considered. dGF = direct green façade, idGF = indirect green façade, LWS = living wall system, model = modelling studies. For both heating and cooling conditions, no statistically significant differences were found.

For the most studied climate regions it was possible to define a range of temperature differences between bare and greened walls (Figure 10). For this, all green wall types were considered (GF and LWS). Overall, it can be seen that greened walls are always cooler in summer and slightly warmer in winter. This confirms the findings that green walls are able to mitigate temperature extremes of building walls.



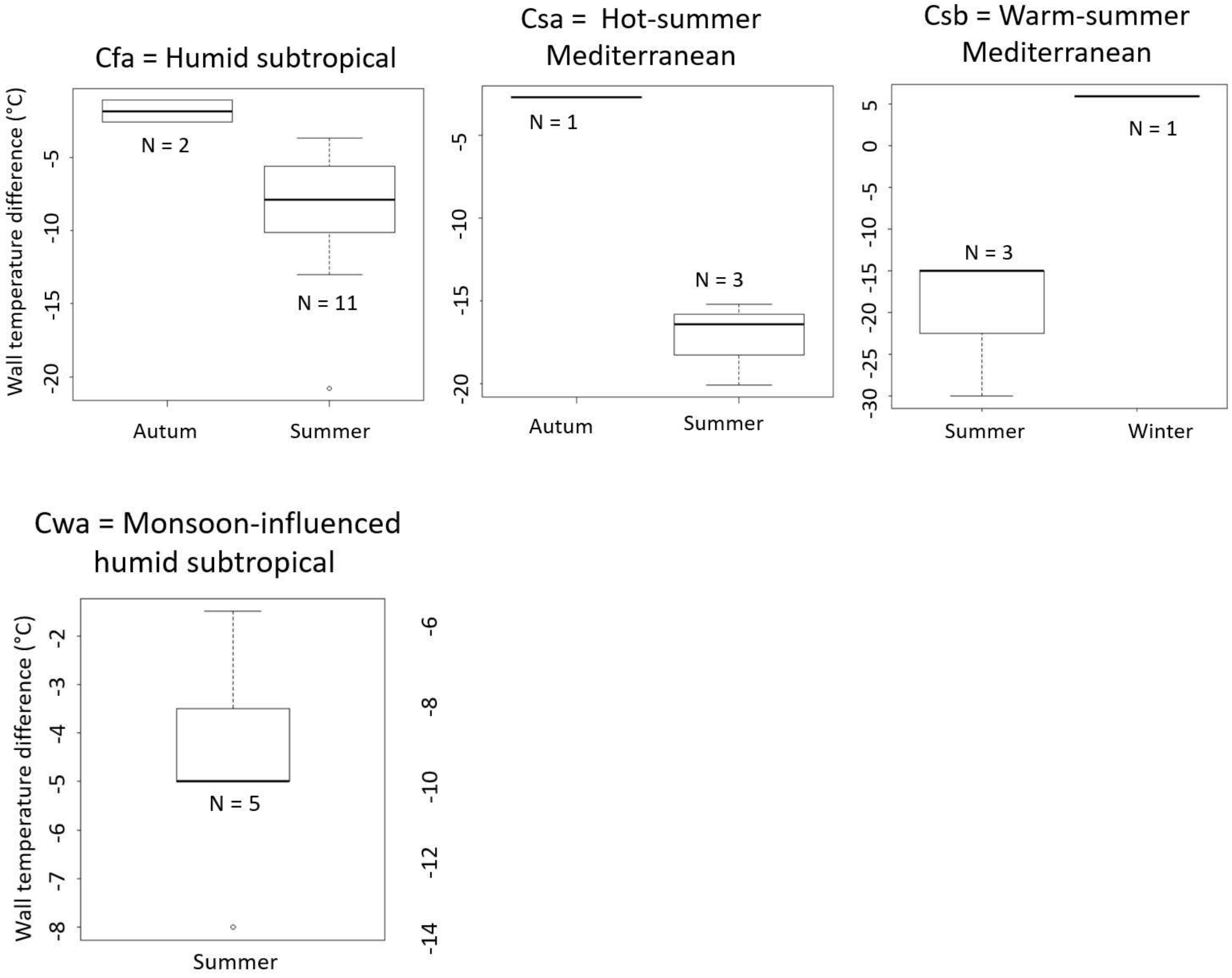


Figure 10: Temperature differences between bare and greened walls (greened wall temperature – bare wall temperature) (°C) for different climate types, indicated with Köppen Climate classification and seasons.

Some general conclusions can be drawn for green walls and their cooling mechanisms. Firstly, shading is considered the most important factor for cooling. It would be interesting to put more focus on the amount of plant cover needed to obtain a maximum shading potential, above which additional plant coverage would be superfluous. Furthermore, shading only has a direct impact on the underlying building wall, as opposed to evapotranspiration, which can influence the microclimate around the buildings or city districts involved. Because entire greened streets are often not existing in the real world, modelling studies can be used to estimate how much green wall surface is needed to cool the local environment through evapotranspiration. Considering insulation, LWS have better properties than green façades. This insulation is most important in winter season or in cold climates.

As previously stated, green walls can have a mitigating effect on the UHI effect, but on the other hand, if poorly implemented, they can even exacerbate the situation. This is the case when buildings in a hot climate cannot cool down at night because the vegetation acts as an insulator, or when, in winter or cold climate, vegetation prevents the building to heat up because of shading. However, in most studies, even these more negative effects do not seem to outweigh the advantages of green walls.

3.2 Major parameters to consider

Many factors play a role in the functioning of a green wall and they are often not sufficiently described in publications. **WLAI** can be considered as the most important parameter, because it determines how much plant coverage there is on a wall. In an ideal situation, this is considered as a dynamic parameter, variating in time and thus including seasonal variability. The mechanical system used to support the green wall can also be important and, furthermore, for LWS the kind of **substrate** should be reported. **Climatic differences**, **season** and **orientation** also play a major role. Environmental temperatures are also sometimes not reported. Furthermore, some studies do not specify plant **species**, which all have their own morphological and physiological characteristics. Several authors suggest that smaller leaves perform better in terms of cooling.

Moreover, there is a strong need for a common way to assess temperature differences. Only a limited number of papers considered the thermal effect of green walls in terms of both the outdoor and indoor air temperature. Measurements should cover all temperature regions (outdoor ambient, outer wall surface, inner wall surface and indoor ambient) and ideally the energy savings for heating and cooling.

Furthermore, experimental designs should be uniformed in order to replicate them under different circumstances, like testing in different climate types, seasons and for different GW and LWS types, and using for example a generic white brick wall, so that obtained ΔT data can be compared and better interpreted.

Replication is also an issue: most experiments are performed only once or sometimes measurements are repeated, but on the same green wall. Researchers are obviously restricted to the available green walls, but repeatable experiments in climate chambers or wind tunnels or common gardens can also be considered and recommended. Urban design also plays a major role in how green walls can cool the local environment, but is rarely included in current modelling studies. Optimisation of both green and grey infrastructure is needed to obtain the most efficient result.

Finally, the building's cladding and insulation materials should be accounted for when constructing a green wall. Green walls cannot replace insulation materials, but they can be employed as an additional insulation layer for buildings with energy efficiency problems (i.e. low heat resistance). Green walls can therefore be implemented in new buildings as well as applied onto existing constructions. In addition, a comparison of the green wall with other types of façade cladding would yield in valuable information.

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