Overcoming the barriers to green walls in urban areas of the UK

Thesis submitted in partial fulfilment for the degree of Doctor of Engineering

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Declaration:

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

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Abstract

Green infrastructure is seen as a tool to mitigate a host of environmental challenges in urban areas. Vertical greening solutions such as direct greening are gaining popularity due to relatively low cost and the fact that they have a minimal ground footprint. There are still, however, a range of barriers to their uptake, including worries about potential wall damage (physically and via RH increase). This research had sponsors from multiple disciplines and as such covers a wide range of topics aimed at reducing barriers to installations of direct greening.

The impact of several popular and widely-used plant species (*Hedera helix* (English ivy), *Parthenocissus tricuspidata* (Boston creeper), and *Pileostegia viburnoides* (climbing hydrangea)), on the internal/external temperature and relative humidity (RH) of replicated experimental model 'buildings' (three per plant species, plus bare buildings) was studied over two summers and winters. All the plant species reduced both the air temperature internally/externally during the summer daytimes by at least 1 ^{o}C (*Hedera* produced the greatest cooling effect internally and externally, 7.2 ^{o}C and 8.3 ^{o}C reduction, respectively). All plant species reduced the daily 'variation' (morning to afternoon) in external RH, and external and internal temperature during summer (*Hedera* reduced variation most and *Pileostegia* least). During night-time, foliage maintained a higher temperature on the external building surface which could reduce the risk of freeze-thaw damage in winter. Additionally, while all plants increased the external RH around the building envelope, that increase should not transfer internally in buildings designed to current standards as the walls include protective layers such as damp-proof membranes.

The 'buildings' were then modelled using building energy simulation software (IES), which accurately simulated the bare 'buildings' in both summer and winter with a weather file containing the data for the local weather. Model validation was also performed for a *Hedera helix* layer based on data from experiments and literature, which was accurately simulated for both summer and winter conditions (mean standard deviation between the simulated and experimental internal temperatures was ± 2.03 ^{o}C for bare buildings, and ± 1.74 ^{o}C for *Hedera*-covered 'buildings'). The simulation of a *Hedera helix* layer will allow energy savings to be calculated in the future from the use of direct greening in retrofits and new builds.

Experiments on the management of a widely spread, but often misunderstood plant species, *Hedera* (ivy), were also conducted. *Hedera* aerial root attachment was prevented or reduced (by at least 30%) by altering wall surfaces through application of copper and zinc sheets and meshes or silane-based anti-graffiti paints. Furthermore, a combination of root restriction and water deficit reduced aerial root number by 88%. This could significantly ease ivy pruning and other management, alleviating the fears around its potential damage to wall surfaces.

Finally, a desktop study into the practicalities of increasing direct greening was conducted, whereby an overview of the green wall industry showed that it is growing, as is the understanding and acceptance of the benefits of direct greening in the UK. Both life cycle assessment and cost-benefit analysis show that direct greening is sustainable in the UK. Regarding increasing green wall uptake, there is currently no mandatory policy in place in the UK; however, a combination of non-mandatory policies and new funding streams for green infrastructure are working well and should continue to increase green wall uptake and installations.

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List of symbols and abbreviations

Abbreviations

ACH	Air changes per hour
ALGG	All London Green Grid
ANOVA	Analysis of variance
BID	Business improvement district
BREEAM	Building Research Establishment Environmental Assessment Method
BST	British summer time
BVOC	Biogenic volatile organic compound
CAD	Computer-aided design
CAZ	Central activities zone
CBA	Cost-benefit analysis
CDT	Community development trust
CE	Controlled environment
CIBSE	Chartered Institute of Building Services Engineers
CIL	Community infrastructure levy
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent
d.f.	Degrees of freedom
DPC	Damp-proof course
DPD	Development plan document
DPM	Damp-proof membrane
E	East
EngD	Engineering Doctorate
EOT	Equation of time
EU	European union
FAR	Floor area ratio
GFA	Gross floor area
GHG	Greenhouse gas
GI	Green infrastructure
GMT	Greenwich mean time
GR	Green roof
GSF	Green space factor
HDPE	High density polyethylene
HVAC	Heating ventilation and air conditioning
IES	Integrated Environmental Solutions
IRGA	Infra-red gas analyser
IHE	Institutions of Higher Education
K-value	Thermal conductivity
L	Left
LAT	Local apparent time
LCA	Life cycle assessment
LEED	Leadership in Energy and Environmental Design
LEN	Low emission neighbourhood

LMT	Local mean time
log.	Logarithmic
LSD	Least significant difference
Ltd.	Limited company
LWS	Living wall system
MO	Meteorological observatory
N	North
NGO	Non-governmental organisation
NHS	National Health Service
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
NUS	National Union of Students
O_3	Ozone
OSB	Oriented strand board
plc.	Public limited company
PM	Particulate matter
$PM_{2.5}$	Particulate matter <2.5 µm diameter
PM_{10}	Particulate matter <10 µm diameter
PVC	Polyvinyl chloride
R	Right
R-value	Thermal resistance
Ra	Surface roughness
RH	Relative humidity
RHS	Royal Horticultural Society
RIBA	Royal Institute of British Architects
ROI	Republic of Ireland
S	South
SC	Site coverage
SD	Standard deviation
SHC	Specific heat capacity
SMC	Substrate moisture content
SO_2	Sulphur dioxide
SPG	Supplementary planning guidance
Sp./Spp.	Species (singular/plural)
TfL	Transport for London
U-value	Thermal transmittance value
UGF	Urban greening factor
UHIE	Urban heat island effect
UK	United Kingdom
UoR	University of Reading
USA	United States of America
UTC	Co-ordinated universal time
W	West
WHO	World Health Organisation
WLAI	Wall leaf area index

Mathematical symbols

A	Net carbon dioxide assimilation
c	Correction factor (for daylight savings)
C(t)	Concentration of a gas at time t
C_0	Concentration of a gas at time 0
C_b	Background concentration of a gas
G_n	Direct solar radiation measured on the normal plane
g_s	Leaf stomatal conductance to water vapour
h	Local hour angle of the sun
I_d	Diffuse solar radiation measured on the horizontal plane
I_G	Global solar radiation measured on the horizontal plane
I_O	Extra-terrestrial solar radiation measured on the horizontal plane
J_d	Julian day angle in degrees
J_r	Julian day angle in radians
k_d	Diffuse fraction
k_t	Clearness index
t	Time
R^2	Coefficient of determination

Greek Symbols

δ	Solar declination angle
θz	Zenith angle
λ	Longitude
λR	Longitude for Reading
Λ	Air changes per hour
φ	Latitude

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Chapter One

Introduction and literature review

This chapter will provide information on environmental issues within the urban landscape and how green infrastructure, particularly green walls, can be used to address challenges such as the urban heat island effect (UHIE), poor air quality, and surface water flooding (see sections 1.1 and 1.2.4). The literature on *Hedera* (ivy), a popular but often 'misunderstood' green wall plant, will then be reviewed including information on the barriers to its installation, its mechanisms of attachment and options for control through alterations to the wall structure and the plant management (see sections 1.3 and 1.4). In addition, the simulation of green walls to predict indoor temperatures and related energy savings for a variety of climates, will then be briefly covered in section 1.5. The literature review will finish by exploring current building regulations with respect to structural greening, and the economic and environmental sustainability of green walls, along with the impacts of policies and incentives on installation uptake (see sections 1.6 and 1.7). Finally, the aim and objectives of this project will be outlined in section 1.8 along with the scope of the research.

This thesis will cover a broad range of topics in order to fulfil the requirements of various stakeholders in the project: two industrial funders (Sutton Griffin Architects and Royal Horticultural Society, RHS) along with an academic one (Engineering and Physical Sciences Research Council). It is hoped that this work on the alteration of relative humidity (RH) by dense foliage will allay concerns regarding the use of climbers such as *Hedera* in structural greening, as the benefits of its use outweigh potential negatives so long as the foliage is pruned. Additionally, the validated computer model for the plant layers will provide future users a basis for demonstrating potential energy savings from the use of *Hedera* around a variety of buildings. Furthermore, it is hoped that the work on policy and incentivisation will provide useful background to those seeking to increase the number of green wall installations across Britain.

Ivy management techniques have been studied in response to the needs of the landscape and architecture sectors, to which one of the sponsors of this study, Sutton Griffin Architects, belongs.

1.1 Urban environmental challenges and green walls[1]

There has been a move to include the concept of ecosystem services in urban space development (to take advantage of the self-regulating tendency of natural processes), which is based on evidence that incorporating biomimicry and greening into structures may address some of the problems currently facing built-up areas (Grant, 2012, Dover, 2015).

One such example of a problem is the urban heat island effect (UHIE) where the mean annual temperature inside an urban development can be 1-3 ^{o}C higher than the surrounding rural area (Oke, 1982, Bailey et al., 1997, Grimmond, 2007). The UHIE occurs as high buildings alter the air flow and materials with low albedo and high thermal mass (which absorb solar radiation during the day and then emit it as heat at night), are used (Oke, 1982). UHIEs universally affect cities and extensive datasets have been gathered for several including London, UK; Hong Kong, China; and New York City, USA (Gaffin et al., 2008, Kolokotroni and Giridharan, 2008, Xuan and Su-Jong, 2018). Temperature increases of between 1.5 ^{o}C at night (during winter in Hong Kong) and 8.9 ^{o}C during a cloudy summer day in London have been recorded compared to the surrounding rural environment (Kolokotroni and Giridharan, 2008, Xuan and Su-Jong, 2018). The temperature increase due to the UHIE can contribute to, on average 13%, increased cooling requirements compared to comparable rural buildings based on assessments of cities globally (Santamouris, 2014).

The need for thermal comfort can lead to increased energy use to manage temperatures, and in 2006 71% of energy-related carbon dioxide (CO_2) emissions were estimated to be due to urban requirements (Dhakal, 2010), therefore reducing the need to heat and cool buildings will reduce greenhouse gas (GHG) emissions (EPA, 2017). The Kyoto Protocol saw nations that ratified the treaty, pledged to reduce annual GHG emissions by an average 5% compared to 1990 emissions (United Nations Framework Convention on Climate Change, 2019), hence it is important to find as many cost effective ways to reduce those emissions as possible.

Furthermore, more than 80% of urban areas globally, have higher concentrations of air pollutants than recommended by the World Health Organisation (WHO, 2016), which include nitrogen oxides (NO_x) and particulates. Additional problems in urban areas are surface water flooding due to large areas of impervious surfaces with high concentrations of properties using drainage systems with limited capacity (Kaźmierczak and Cavan, 2011).

[1] Sections of the early drafts from the Literature Review formed the basis of a book chapter written in conjunction (50:50) with Dr Tijana Blanuša, (Blanuša and Thomsit-Ireland, 2017 p. 85).

[2] This chapter was published as a paper, Thomsit-Ireland et al. (2016), for which the work was all my own.

Urban greening or green infrastructure (GI: which involves various forms of green space such as green roofs/walls, parks, street trees and gardens) provides some methods to mitigate problems facing towns and cities (see section 1.2.2). Urban space is at a premium and hence forms of GI that require minimal additional space have greater priority. An example is green walls as they are applied vertically, and are already part of the building footprint, requiring minimal additional ground space to implement.

1.1.1 Green walls

Green wall systems include direct greening, indirect greening and living walls (Perini et al., 2011b). Direct and some forms of indirect greening can also be termed green façades; in direct greening, a self-attaching climber uses a building façade substrate as support whereas indirect greening includes some form of engineered solution (such as trellises, wires or modules), thus providing a gap of insulating air between the building and the plant. If irrigation and nutrient supply are required, the system is considered a living wall system (LWS); LWS are constructed with planter boxes or geotextiles and do not require climbing plants but may incorporate them. An LWS may, however, be comprised of plants in deep planters (for example, 1-4 m x 0.5 m x 0.5 m) such as *Hedera* screens and green hoarding, alternatively if shallower planters or geotextile modules are used, then plants for intensive green roofs are suitable (Perini et al., 2011b).

Plants are chosen for green walls based on their characteristics (including leaf and flower shapes and colours), and building attributes (such as aspect and colour). Some climbing plants that are frequently used in green façades are identified in Table 1.1 (Dunnett and Kingsbury, 2008). When choosing plants for south facing façades on buildings in the northern hemisphere, deciduous species such as *Parthenocissus* spp. or *Campsis* spp. are preferable, as leaf loss allows for winter solar gains (Grant, 2006), while increased leaf area in summer provides a cooling effect through shading and evapotranspiration (Cameron et al., 2014).

Table 1.1 Planting requirements, growth rate, and additional notes of climbing plants commonly used in green façades based on plant data from Royal Horticultural Society (2018a)

Plant	Sun/Shade Aspect, Exposure	Evergreen/ Deciduous	Expected height range after X years	Notes
Pileostegia viburnoides	Sun/Shade, any aspect/exposure	Evergreen	4-8 m after 10-20 years	Cream coloured flowers, self-attaching
Trachelospermum jasminoides	Sun, S/W/E sheltered	Evergreen	4-8 m after 5-10 years	Initial support then self-attaching
Parthenocissus tricuspidata* and *P. quinquefolia	Sun Shade, any aspect/exposure	Deciduous	More than 12 m after 5-10 years	Excellent autumn colour foliage, self-attaching
Hedera helix	Sun/Shade, any aspect/exposure	Evergreen	8-12 m after 10-20 years	Self-attaching
Hedera hibernica	Sun/shade, any aspect/exposure	Evergreen	8-12 m after 5-10 years	Tolerates sun better than *H. helix*, self-attaching
Campsis radicans	Sun, S/W, sheltered	Deciduous	8-12 m after 10-20 years	Orange, yellow or red flowers, self-attaching
Hydrangea anomala* subsp. *petiolaris	Sun/shade, any aspect, sheltered	Deciduous	More than 12 m after 10-20 years	Heart shaped leaves; white lace-cap flowers, supported climber
Schizophragma hydrangeoides	Sun or partial shade any aspect/exposure	Deciduous	8-12 m after 10-20 years	White flowers, supported climber
Euonymus fortunei	Sun or partial shade any aspect/exposure	Evergreen	1-2.5 m after 5-10 years	Has aerial roots but may need some support

Hedera is extensively used for green façades in both the UK and Europe, and grows well with minimal support in the urban environment (see section 1.4.1), yet remains a misunderstood plant. *Hedera* easily establishes itself naturally around unmaintained walls and structures (Figure 1.1), and is being installed around the perimeters of schools, construction sites, and homes to capture pollutants, thus reducing the impact of vehicular emissions and dust (Figure 1.2; Ottelé et al. (2010), Sternberg et al. (2010b), Mobilane UK Ltd. (2018c), Tremper and Green (2018)).

Figure 1.1 L-R: *Hedera* climbing over railway supports in London and Vienna (Photographs by Faye Thomsit-Ireland)

Figure 1.2 *Hedera* screens at Bowes primary school, Enfield, picture from: Airqualitynews.com (2018)

The pollutant capture rates and thermal impact (especially summer cooling) of *Hedera*, have been studied in-depth (Köhler, 2008, Sternberg et al., 2010b, Pérez et al., 2011a, Ottelé and Perini, 2017). *Hedera* can also provide some insulation effect in winter, increasing the minimum temperatures at the wall surface (Bolton et al., 2014, Cameron et al., 2015, Ottelé and Perini, 2017). There are, however, anecdotally, many concerns regarding the vigour of *Hedera* growth and its potential to damage buildings which will be discussed further in section 1.3. Fortunately, the attachment mechanisms of *Hedera helix* (English ivy) have been thoroughly studied (Zhang et al., 2008, Melzer et al., 2010, Burris et al., 2012), indicating ways to counteract aerial root attachment. Many *Hedera* species are cheap to purchase and grow rapidly, which makes them a viable option for green walls. Therefore the focus of much of this thesis is on direct greening especially with *Hedera*, and the benefits and problems associated with its use.

1.2 Ecosystem services derived from green walls

1.2.1 Ecosystem services and disservices

Ecosystem services have been defined as the benefits that humans derive, either directly or indirectly, from healthy ecosystems' functions; an ecosystem relates to the combination of biological organisms and their environment (Costanza et al., 1997, Willis, 1997). Ecosystem 'disservices' are defined as ecosystems' functions that are negatively perceived for human well-being' (Lyytimäki and Sipilä, 2009). Green walls are increasingly considered to perform ecosystem functions that may be advantageous such as trapping pollutants, moderating temperature, and improving quality of life (Wang et al., 2014) or harmful including invasiveness and allergenicity (Gómez-Baggethun and Barton, 2013, Cameron and Blanuša, 2016).

Benefits arising from green façades include increased thermal insulation by decreasing the overall heat transfer through the walls by 10-33%, depending on the initial U-value of the wall (Ottelé, 2011), and reducing peak cooling loads by up to 28% in a low-rise building in China on a clear summer day, for example (Di and Wang, 1999). Green walls also intercept and retain a proportion of rain flow (Figure 1.3), easing the water drainage issues associated with peak rainfall and adding a layer of bio-protection for old buildings (Sternberg et al., 2010a). Furthermore, green walls increase urban biodiversity by providing a habitat for insects, gastropods, birds and mammals (Metcalfe, 2005, Chiquet et al., 2013). Lastly, greening urban areas can significantly increase mental well-being of residents (Kuo and Sullivan, 2001) and perceived building value (White and Gatersleben, 2011).


Figure 1.3 Precipitation intercepted by *Hedera* leaves (Photographs by Faye Thomsit-Ireland)

Potential ecosystem 'disservices' produced by green wall vegetation include allergens from plant pollen/hairs and for *Hedera* specifically handling the plant during pruning can cause skin irritation (Paulsen et al., 2010, Gómez-Baggethun and Barton, 2013). Biogenic volatile organic compounds (BVOC) emissions are released by most plants and can be particularly harmful when released in the presence of high concentrations of nitrogen oxides (NO_x; which are frequently found in the urban environment), as they contribute to the formation of ozone (Calfapietra et al., 2013). Ozone is a GHG, respiratory irritant, and contributes to air pollution such as photochemical smog (NRC, 1991, Niinemets and Peñuelas, 2008). While isoprene is the most abundant BVOC (Calfapietra et al., 2013), there have been no high concentrations of isoprene emissions associated with *H. helix* (Hewitt and Street, 1992). In addition to damage to buildings by plant roots, which are described in perceived barriers (see section 1.3), a final purported disservice associated with dense green shrubs and plants such as *Hedera* is the potential to hide criminals and pests (Köhler, 2008, Gómez-Baggethun and Barton, 2013, Cameron and Blanuša, 2016).

1.2.2 Air temperature moderation by green walls

The urban heat island effect (UHIE; section 1.1) occurs not only due to the construction of the built environment, but also due to heat released from traffic, industrial activity, and energy sources in the urban environment such as generators and air conditioning unit outlets (Grimmond, 2007, Kershaw et al., 2010). The UHIE can be mitigated by lighter-coloured urban structures (for example, white, reflective roof surfaces and pavements) which increase albedo and therefore reflect more energy (Akbari and Konopacki, 2005). Vegetation not only reflects more energy than built structures in most cases, but also provides local cooling through shading and evapotranspiration (Cameron et al., 2012). Evapotranspiration, which is unique to plants, is notable as energy is consumed through the process of water loss from plant tissues, without heating the surrounding surfaces (Taiz and Zeiger, 1998). Thus a wall covered in vegetation will not only reflect more energy than a dark, bare wall, but will contribute additional cooling through latent heat loss as long as the plants are freely transpiring and have sufficient water availability (Cameron et al., 2014). Additionally, vegetation on walls reduces the external surface temperature of a building, thus reducing the amount of heat that is re-radiated into the surroundings. Some studies on green walls, however, have shown that there is no measureable temperature reduction in front of a greened wall (Hoelscher et al., 2016) or at a distance of 1 m from the wall (Perini et al., 2011a); the lack of measureable temperature difference may occur through air mixing due to wind (Hoelscher et al., 2016).

1.2.3 Energy savings from reduced space heating and cooling requirements due to influences on the building microclimate by green walls

The global energy demand for air conditioning is predicted to increase exponentially over the coming decades, overtaking heating demand circa 2060 (Isaac and van Vuuren, 2009). However, green walls, such as ivy cladding, can reduce the need for air conditioning, by stabilising the microclimate around structures, and by providing passive cooling via evapotranspiration and shading.

Observations made on a single, sunny, clear, low-wind day in July in China showed that the ivy layer on the wall reduced the total solar gain to the adjacent room by 75%, resulting in a 28% reduction in air conditioning use to maintain the desired temperature (Di and Wang, 1999). Additionally, recent research in a temperate climate, on ivy-clad model brick cuboids, indicated that a 21 to 37% reduction in energy use for winter heating could be achieved (Cameron et al. 2015). The insulating effect of ivy over a wall in winter was also observed using a thermal imaging camera, which detected a 3 ^{o}C increase in wall temperature behind the ivy compared to the bare wall (Köhler, 2008). The extent of temperature changes measured on a wall, however, is dependent on cover depth and species, exposure, and aspect (Sternberg et al., 2011a).

Hedera cladding stabilises the microclimate around the wall over which it grows; reducing the range of temperatures recorded on building surfaces by up to 50% over the course of a year (Sternberg et al. 2011a). Furthermore, over 12 months, measurements on ivy-covered stone walls across several historic sites in England showed that the ivy coverage significantly reduced the mean daily maximum temperatures on the wall surface by up to 25% and increased the mean daily minimum temperatures by 10% (Sternberg et al. 2011a). If greening systems are implemented to stabilise building façade temperatures, the evapotranspiration properties of species utilised must be considered. When plants become water stressed, evapotranspiration typically ceases and the leaf temperature can start increasing, however, the surface covered by the plant remains cooled through shading (Blanusa et al., 2013, Cameron et al., 2014). Plant species have different evapotranspiration rates, which were observed to influence cooling (of a wall in a controlled environment) by varying amounts. When compared to controls, *Jasminum officinale* (common jasmine) and *H. helix* reduced temperatures measured on a wall, by 4.3 ^{o}C and 7.3 ^{o}C respectively (Table 1.2; Cameron et al. (2014)). Additionally, the cooling properties of many other deciduous plants including *Fallopia baldschuanica* (Russian vine), *Parthenocissus quinquefolia* (Virginia creeper), and *Wisteria sinensis* (Chinese wisteria) have been studied as part of systems such as double-skin façades or bioshaders (Ip et al., 2010, Pérez et al., 2011a) and indirect greening (Hoelscher et al., 2016). These studies found that when the species above covered the adjacent wall, temperatures were lowered by up to 5 ^{o}C in the room (Ip et al., 2004), by up to 15 ^{o}C at the wall surface (Pérez et al., 2011a), and reduced the solar transmission by up to 90% (Ip et al., 2010, Pérez et al., 2011a).

Table 1.2 Cooling compared to controls due to plant evapotranspiration and shading by different plant species from Cameron et al., 2014.

Species	Cooling by evapotranspiration (^{o}C)	Cooling by shading (^{o}C)	Total cooling from plant and media (^{o}C)
Hedera helix	1.3	4.7	7.3
Stachys byzantina	3.0	3.5	7.6
***Fuschia* 'Lady Boothby'**	3.2	1.8	5.5
***Jasminum officinale* 'Clotted Cream'**	0.9	2.4	4.3
***Lonicera* 'Gold Flame'**	1.8	2.9	5.5
Prunus laurocerasus	2.9	3.0	6.3

Hoelscher et al. (2016) reported that, to provide maximum passive cooling, plants in some green façades must be irrigated by up 2 $Lm^{-2}d^{-1}$ during high temperature days. This was complemented by further research on an LWS during summer in the Mediterranean, where evapotranspiration rates of plants including *Hedera* were measured. Evapotranspiration measured from the plants was up to 1% more per hour than evaporation from the LWS geotextile irrigated bare panel, however, different plant species displayed similar evapotranspiration rates (Perini et al., 2017a). Additionally, evapotranspiration rates and water use were evaluated for *Parthenocissus tricuspidata* (Boston/Japanese ivy/creeper) and *H. helix* which showed that both species displayed similar water use per leaf area with an average 0.5 $Lm^{-2}d^{-1}$ required and evapotranspiration accounted for approximately 18.5% of the cooling during the day (Hoelscher et al., 2016). However, when compared to other species (*Stachys byzantina* (lamb's-ear), *Prunus laurocerasus* (cherry laurel), and *Fuchsia spp.*), *H. helix* only produced 1 ^{o}C of cooling by evapotranspiration (Cameron et al., 2014). These studies show that the plant choice and water availability matters when choosing to green a wall either directly or indirectly. A compromise may, however, be necessary between the water requirements of the chosen plants and the cooling benefits they provide.

It is also necessary to consider the structure of both greening systems and the buildings to which they are applied. Adding a 160 mm vegetative layer was estimated to improve the thermal transmittance (U-value) of a building by 33% from an initial U-value of 1.5 $Wm^{-2}K^{-1}$. However, as the base building insulation improved to 0.3 $Wm^{-2}K^{-1}$ improvement in the U-value due to greening decreased to only 10%, 0.27 $Wm^{-2}K^{-1}$ (Ottelé, 2011). This shows that the benefit of vegetative greening reduces as the building construction improves; therefore as may be expected vegetative greening has the greatest impact on poorly insulated buildings.

Research into the thermal resistance (resistance to heat flow) or R-values of direct and indirect greening, showed that plants (a 200 mm thickness of *Hedera*) may have different thermal resistances in the summer and winter (Ottelé and Perini, 2017). The thermal resistance was derived from temperature measurements and was 0.66 m^2KW^{-1} and 1.10 m^2KW^{-1} for direct and indirect greening respectively in summer and 0.18 m^2KW^{-1} for both forms of greening in winter (Ottelé, 2011, Ottelé and Perini, 2017). This research showed that even if plants produce different thermal resistances depending on the season and external temperature, the thermal resistance of the building wall was still improved by vegetation. In contrast, in a building energy simulation based on winter in northern Portugal, when a living wall system (planted with evergreen species), was applied to the south wall of a building, the winter heating requirements were increased by between 35% and 81% as the plants inhibited the solar gains to that wall (Carlos, 2015). All other wall aspects, however, benefited from the greening, thus emphasising the benefits of using deciduous vegetation on south walls to maintain solar gains in winter. Furthermore, the surface area of green coverage was found to be more important for cooling than the depth of the cover; however, as ivy ages, it changes shape so its thermal benefits may also alter over time (Köhler, 1993).

A final concern, regarding heat loss from buildings, is the impact of wind velocity. A 200 mm thickness of *Hedera* covering a wall was found to reduce wind velocity to less than 0.5 ms^{-1} inside the foliage and by the wall (Rath et al., 1989). Additionally, air velocity between *Hedera*-cladding and between an LWS and the wall surface was a fifth of that measured 100 mm in front of the façade, though for indirect greening with a 200 mm gap the air velocity next to the wall was only two thirds of that measured 100 mm in front of the façade (Perini et al., 2011a). These two studies suggest that green walls significantly reduce the air velocity next to the building envelope; albeit subject to a maximum gap size, of 40-60 mm. As green walls reduce air flow around buildings they may have a similar effect to a well-constructed shelter belt, which has indicated winter heating savings of 11-18% for poorly insulated buildings (DeWalle and Heisler, 1983, McPherson et al., 1988, Liu and Harris, 2008).

1.2.4 Outdoor air quality improvement by vegetation

Industry, transport, agriculture, and domestic combustion all contribute to air pollution, both in gaseous and particulate forms. Gaseous pollutants include sulphur dioxide (SO_2), carbon dioxide (CO_2), ozone (O_3), and nitrogen oxides; NO_x (Godish et al., 2014). Particulates include material from natural sources, hydrocarbon-based power generation, transport (which contributes up to 70% of the air pollution in urban areas (Environmental Audit Committee, 2010)), incineration, and domestic heating (Godish et al., 2014). Particulates represent a specific problem as particles with a diameter <10 µm (PM_{10}) can enter human airways, those <2.5 µm ($PM_{2.5}$) can reach pulmonary air sacs (Godish et al., 2014) and those <0.1 µm enter the blood circulation system (Godish et al., 2014), causing a range of lung and heart problems. Based on 2013 pollution concentrations, 40,000 premature deaths were estimated to occur annually in the UK due to nitrogen dioxide (NO_2) and $PM_{2.5}$ (Royal College of Physicians, 2016).

Consequently, maximum acceptable concentrations of SO_2, NO_x, lead, and PM_{10} have been set by both the European Union and the World Health Organisation; WHO (The Council of the European Union, 1999, WHO, 2006), with warnings to the public and fines of up to £300 million resulting if these are breached (The Council of the European Union, 1999, Environmental Audit Committee, 2010). Several British urban areas, including London, frequently exceed mandatory maximum concentrations of NO_2 and PM_{10} (Environmental Audit Committee, 2010, GLA, 2010). Studies have reported that green façades and trees may be able to mitigate some of these problems by reducing SO_2 concentrations in air between foliage (Rath et al., 1989) and dense patches of roadside forest were found to reduce NO_2 concentrations by an average of 7% or 2.7 µgm^{-3} (Grundström and Pleijel, 2014). However, those results have not been found unanimously (Setälä et al., 2013). In a study comparing different roadside options ability to capture vehicular particulates, green walls reduced emission concentrations alongside roads, however, a wide dense tree-based barrier or a solid barrier plus mature trees behind the barrier provided greater mitigation (Tong et al., 2016). That said, in many cases an ivy covered barrier would provide coverage quickly and cheaply; and would require less roadside space and maintenance than mature trees. Furthermore, when grown indoors, *Hedera helix* has been found to remove volatile organic compounds, including benzene, octane, and toluene) from the air (Yang et al., 2009); however, interior air flow tends to be slower, which may increase plant efficiency in volatile organic compound removal.

Air movement in urban areas is influenced by the structure of buildings and streets, which form 'street canyons', causing the air to circulate and refresh more slowly than if the area is open (Vardoulakis et al., 2003). If a source of pollution exists at the bottom of a 'street canyon', that pollution can become increasingly concentrated, due to air recycling and minimal fresh air circulation (Pugh et al., 2012). Simulations with green walls along 'street canyons' indicate a reduction of 6.4-42.9% for NO_2 concentrations, and 11-62% for PM_{10}, depending on prevailing conditions (Pugh et al., 2012), making them more effective than street trees for air pollutant removal (Pugh et al., 2012). The extent and effectiveness of particulate removal via dry deposition depends on a number of factors, such as the characteristics of plants comprising the green wall (including leaf size and morphology, pubescence, and canopy features), and the physical characteristics of the environment in which the wall is situated including wind speed, temperature, particle size, and gas solubility (Beckett et al., 2000; Freer-Smith et al., 2005; Weber et al., 2014).

There is evidence that plant species and cultivars differ significantly in their capacities to remove various forms of pollutants; rough, hairy surfaces or grass like plants collect more particulates from the air than glabrous plants (Beckett et al., 2000, Speak et al., 2012, Blanuša et al., 2015). Particulate capture features may alter under the influence of pollution, potentially increasing their effectiveness for example, by increasing pubescence length and roughening the surface texture, without impacting plant health (Zhang et al., 2015). The presence of epicuticular wax has also been observed to increase particulate capture (Sæbø et al., 2012, Weerakkody et al., 2017, Weerakkody et al., 2018), though capture rates may be reduced due to wax hydrophobicity (Zhang et al., 2015, Leonard et al., 2016). Albeit the observed reduction of particulate capture on waxy leaves may be a product of experimental approaches, as washing sample leaves may not remove all particules adhered to the wax (Weerakkody et al., 2017). Additionally, there is evidence that combinations of leaf traits may alter the overall performance of the particulate capture of a leaf, as high leaf epicuticular wax content was found to overide the presence of hairs in some tree species (Leonard et al., 2016).

While *H. helix* is classed as glabrous by Shackleton et al. (2012), the undersides of the leaves (especially when young), are hairy (Rose, 1980), so maintaining young shoots through regular pruning could be beneficial for particulate capture. However, leaves' undersides are typified by lower particulate capture rates than the upper sides (Ottelé et al., 2010). Additionally, some hairy-leaved species of *Hedera*, such as *H. azorica* (Azores ivy; Rose, 1980) may also be good candidates for enhanced particulate capture. *Hedera helix* has been found to capture particulates at concentrations between 1.47-2.9 x 10^{10} per m^2 leaf area in heavy traffic areas (Figure 1.4; Ottelé et al. (2010), Sternberg et al. (2010b)). All plant leaves, however, have a finite capacity to capture particulates; after a few months (though rainfall may increase the period), it has been suggested that they become saturated with particles, at which point pruning or washing could refresh sequestration capacity (Shackleton et al., 2012, Speak et al., 2012). This would be a greater issue in places with long dry summers.

Figure 1.4 Dust particles trapped on *Hedera* leaves (Photograph by Faye Thomsit-Ireland)

Removal of CO_2 (a GHG) from the air by carbon sequestration is still being quantified for green roofs and walls (Getter et al., 2009, Chen, 2015, Marchi et al., 2015). In a Mediterranean climate, a simulation indicated that per square metre of a green wall 0.44-3.18 kg CO_{2eq} would be sequestered per year (Marchi et al., 2015) and per square metre an extensive sedum-based green roof could, over two years, sequester 0.38 kg CO_{2eq} (Getter et al., 2009). *H. helix,* which is extensively used in green façades, was shown to be more efficient at converting CO_2 to oxygen per equivalent leaf area than a beech tree (Ottelé, 2011).

1.2.5 Biodiversity support by green walls

Improving urban biodiversity is important due to increasing habitat loss to urbanisation; humans will increasingly need to co-habit with displaced species (Given & Meurk, 2000). Additionally, there are many ecosystem services provided by wildlife, from managing pest outbreaks (Gurr et al., 2003) to providing pollination services (Senapathi et al., 2015).

An American study of green façades with mixed climbers growing over steel mesh, which had a *Parthenocissus* species at 4 of the 10 sites, found 50 arthropods on bare walls compared to 4,407 arthropods on the green walls during the sampling period (Matt, 2012). Green façades primarily covered with *Parthenocissus tricuspidata* had arthropod species suited to dry, warm climates similar to cliffs whereas those found on modular and felt walls preferred damp surroundings. In total 601 adult specimens from 62 spider and beetle species were identified, with the lowest species richness found on bare walls (Madre et al., 2015). Furthermore, studies in the UK comparing green walls (living walls, green screens: a plant typically ivy grown over a trellis, and green façades) and bare walls found significantly more species and adult specimens on the green walls. On green walls, 2,389 spiders (19 species) and 489 snails (7 species) were collected which compared to just 9 spiders (4 species) and 6 snails (2 species) on bare walls (two studies in Chiquet, 2014).

Additionally, over 70 species of arthropods feed on the leaves and a further 70 feed on the flowers of *Hedera*; these organisms then attract additional predatory and parasitic insects (Metcalfe, 2005). A couple of species heavily utilise *Hedera* including the ivy bee (*Colletes hederae*) which is oligolectic for *H. helix* pollen (Bischoff et al., 2005) and the holly blue butterfly (*Celastrina argiolus*) which uses ivy as a larval food plant for the second brood of caterpillars (Figure 1.5a; Beaufoy (1947)). A study showed that *H. helix* provides late season pollen and nectar for several insect groups; wasps were more effective ivy pollinators compared to flies, bristly and hoverflies (Figure 1.5b and c); and bees, solitary bees, bumblebees, and honeybees. Over 55% of visits to ivy flowers were by wasps (Figure 1.5d), which carried the most pollen, were most abundant, and visited more flowers than the other insects monitored (Jacobs et al., 2010). Furthermore, *Hedera* is an important nectar source to insects including honeybees, where a study showed that 80% of honeybee visits to ivy were only to collect nectar (Garbuzov and Ratnieks, 2014). There are, however, concerns about *Hedera* as a food source for honeybees as the honey easily crystallises in cold weather, which can make it harder for honeybees to access the ivy honey during the winter (Rothamsted Experimental Station, 1975, Greenway et al., 1975, 1978).

Figure 1.5 L-R: (a) Holly blue (*Celastrina argiolus*) sheltering in *Hedera* leaves, (b), (c) two fly spp. (*Diptera* spp.), and (d) common wasps (*Vespula vulgaris*) feeding on *Hedera* flowers (Photographs by Faye Thomsit-Ireland)

A further study showed that when bare walls were compared to walls planted with a mix including three *Hedera* species, *Pyracantha* and several deciduous plants, there were 4.5 times more birds present on vegetated walls (on the building roof, wall, and the surrounding vegetation) than those left bare (Chiquet et al., 2013). Ivy fruit is eaten and dispersed by at least 17 species of birds and can provide shelter for other wildlife like bats (Metcalfe, 2005), indicating the importance of ivy in supporting vertebrate wildlife (Metcalfe, 2005). The evergreen nature of ivy makes it attractive to wildlife year-round and provides added benefits compared to deciduous species (Dover, 2015).

These in-depth studies emphasise the importance of green walls in supporting increased bird and invertebrate biodiversity (Figure 1.6).

Figure 1.6 L-R: Orb web spider (*Araneus diadematus*) and scarlet tiger moth (*Callimorpha dominula*) sheltering in *Hedera* (Photographs by Faye Thomsit-Ireland)

1.2.6 Noise reduction by green walls

While there are no statutory limits for noise as an environmental menace, generators of noisy environments, such as construction sites are required to make a practical effort to minimise impact and prevent nuisance (Swindon Borough Council, 2005, Department of the Environment, 2010).

Vegetation attenuates noise, but the attenuation extent is dependent on a number of factors including leaf area and structure, canopy density, depth of cover, plant choice, and type of ground cover (Noble, 1980, Fang and Ling, 2003, Wong et al., 2010b). A simulation of a variety of greening methods indicated that traffic noise is reduced by between 2 and 4 dB for partially or fully greened façades (Van Renterghem et al., 2013), which agrees with a study using greened trellis (Wong et al., 2010b). Outdoor modular living wall systems attenuated noise across multiple frequencies by around 15 dB (Azkorra et al., 2015), however, *Hedera helix* only absorbed 10% acoustic energy compared to other plants such as *Primula vulgaris* (common primrose) which absorbed 60% of the acoustic energy indicating that *Hedera helix* may only be suitable for noise attenuation as the depth of cover and leaf area increases (Horoshenkov et al., 2013). This shows that there is potential for green walls to reduce noise passing through the building they surround and to reduce the reflected noise in the 'street canyon'.

1.2.7 Psychological effects of viewing and interacting with vegetation

By 2011, it has been estimated that over 50% of the global population live in urban areas (The World Bank and The International Monetary Fund, 2013) and that number is increasing. Urbanisation leads to increasing population density in which a higher incidence of depression and psychosis occur (Sundquist et al., 2004). Contact with the natural environment has been found to help human health in myriad ways, from enhancing recovery and reducing dependence on pain relief medication (Ulrich, 1984); to decreasing mental fatigue and aggression (Kuo and Sullivan, 2001). Greened surroundings, even in the form of images, have been found to enhance the effect of exercise by lowering blood pressure (Pretty et al., 2005).

The importance of access to public green spaces is accepted by both UK and Europe; guidelines for an accessible natural green space standard were developed in the 1990s by English Nature and revised in 2010 by Natural England (Pengelly Consulting, 2010). The European Environment Agency provided similar guidelines in 2002 for sustainable development (European Environment Agency, 2002) which acknowledged the importance of green spaces. Therefore providing greenery at the building level may provide both psychological and mental benefits.

1.3 Perceived barriers to the implementation of ivy and other green façades

1.3.1 Building damage

In addition to the many benefits that green façades provide, there are concerns about *Hedera*, primarily regarding its impact on wall integrity. While *Hedera* is not known to cause subsidence (Department for Communities and Local Government, 2011), it can root into weakened historic walls or buildings that have not been maintained and it can lift blocks of stone off walls by growing under them (Viles et al., 2011). Additionally, sidings, tiles or loose fitting cladding are at risk from *Hedera*, as it can grow under the surfaces and lift them (Dunnett and Kingsbury, 2008). Furthermore, external wall render must have sufficient strength to support the weight of the plants (along with any rain/snow loading), otherwise they could pull or crack the external plaster/render (Rath et al., 1989). Finally, depending on the removal methods employed, *Hedera* can leave 'scarring' on surfaces including those that are painted, and/or made of wood or masonry (Figure 1.7).

Figure 1.7 L-R: *Hedera* 'scarring' on wood, painted walls, and masonry (Photographs by Faye Thomsit-Ireland)

As a second concern, if *Hedera* is not pruned and causes damage to the roof, guttering, sidings or cladding (Figure 1.8a), the building may become damp, because the structural integrity has been impaired (Douglas & Noy, 2011). Additionally, self-attaching climbers (such as *Hedera*), can cause damage to buildings by bridging engineering features designed to prevent water ingress such as drip grooves (Figure 1.8b). Drip grooves encourage water to coalesce at the groove and fall away from the structure, rather than running towards building fabric. Despite these concerns, it is generally accepted that if the building construction used ‘Portland cement’ in the mortar rather than lime and the structure is of sound construction, without cracks or damp, it should be suitable for *Hedera* and other climbing plants to attach.

Figure 1.8 Top to bottom: (a) *Hedera* growing in and around guttering and over vulnerable tiles, additionally (b) *Hedera* growing in drip groove (Photographs by Faye Thomsit-Ireland)

1.3.2 Prolonged high relative humidity around the building envelope

Another frequent concern with wall greening is the impact that vegetation may have on the wall and interior relative humidity (RH), therefore the risk of mould development. Plants release water vapour through evapotranspiration into the air around them (thus increasing humidity), especially in summer (Ip et al., 2004, Ottelé, 2011); meaning if grown across a window to provide shade, plants may increase humidity in the room that connects to that window (Ip et al., 2004, Ottelé, 2011).

Ottelé and Perini (2017) measured the impact of ivy cladding, among other greening treatments, in a controlled environment (CE); during the ‘summer setting’ the RH in the wall cavity decreased, while the internal RH increased. Conversely, during the ‘winter setting’ the RH in the wall cavity for all greening treatments (direct, indirect, planter LWS, and felt LWS) approached 100%, while the internal RH decreased, though no explanation was given for this (Ottelé, 2011). However, the increase in RH in the wall cavity during winter is likely to have been a factor of the experimental design as the CE had no mechanism to release accumulated water vapour (Ottelé, 2011). In contrast, Rath et al. (1989) found no difference in the moisture content of exterior plaster and brickwork between December and July of *Hedera* and *Parthenocissus* greened walls compared to a wall with no greening. While there has been a historic debate regarding whether *Hedera* 'causes' or 'cures' damp walls (Taddyforde et al., 1877, Muckley, 1886), it has been noted that if a wall is already damp, the causes of the water ingress must be first remedied and the wall allowed to dry. This must be done before *Hedera* or any other vegetation is planted in front of the wall, as the presence of plants reduces the rate of water evaporation from the wall surface. It may be, however, that any increase in RH due to evapotranspiration by the foliage is offset by precipitation interception. Therefore, buildings that were not damp before greening and are constructed soundly without cracks and other defects, should be fine thereafter.

Several management solutions regarding the building envelope could further reduce the occurrence of damp. At the base of most buildings, 150 mm (or two to three brick courses) above ground level, there is an impermeable layer called the damp-proof course (DPC). The DPC can be made from many impermeable materials such as copper, lead, slate or plastic membrane (Foster & Greeno, 2013). The DPC prevents moisture rising via capillary action from the soil into the building (Foster & Greeno, 2013). If however, damp foliage or soil covers the DPC around a building, there is a risk of moisture entering the building (Howell, 2003). Therefore, soil height and any planting around a house should always be 150 mm below the DPC and any organic matter accumulation around the DPC should be removed annually. Additionally, cavity walls are frequently ventilated using weep vents (McKay, 2015), although the absence of cavity ventilation may indicate that a building wall is not suitable for direct greening.

1.4 *Hedera* (ivy)

1.4.1 Biology of *Hedera*

The genus *Hedera* contains around 16 species of pre-dominantly evergreen, creeping and climbing plants (Ackerfield and Wen, 2003) which tend to grow naturally in shady, sheltered areas (Metcalfe, 2005). The native geographical spread of *Hedera* ranges from Macaronesia in the west, through Europe, to Afghanistan, then through the Himalayas, and onto Japan in the east. There are six species defined geographically, *Hedera rhombea* (Japanese ivy), Japan and Korea; *H. nepalensis* (Himalayan/Nepal ivy), Himalayas; *H. colchica* (Persian/Colchis ivy) and *H. pastuchovii* (Iranian ivy), Turkey to Afghanistan; *H. algeriensis* (Algerian ivy), North Africa; and *H. helix* southern Scandinavia, through Europe, to the Caucasus and West Russia (McAllister and Marshall, 2017). While *Hedera* is not native to the Americas or Australia, it has spread widely (Rose, 1980). *H. helix, H. hibernica* (Irish/Atlantic ivy)*, H. colchica, H. algeriensis, H. canariensis* (Canary ivy), *and H. nepalensis* are the primary horticultural species in the UK (Rose, 1980). Species of *Hedera* grow in many countries across the world, making it a highly adaptable form of direct greening that can be grown virtually anywhere.

Most *Hedera* species have juvenile (Figure 1.9a) and mature phases (Figure 1.9b; Metcalfe (2005)). The juvenile plant climbs with adventitious roots and the mature form is a shrub, which can grow to up to 30 m tall, with woody stems up to 250 mm thick. *Hedera* is able to reproduce vegetatively through the adventitious roots on the juvenile stems, which became 'true roots' after prolonged contact with soil (Melzer et al., 2012). The juvenile form is the first to colonise walls, and as it has adventitious roots, it is the form most likely to cause building damage through exploitation of cracks and deviations in the brickwork. The mature phase reproduces sexually with flowers, fruit, and seeds (Metcalfe, 2005), and *H. helix* takes 10 years to flower in natural conditions (Clark, 1983). The flowers are minimal (providing nectar to insects between September and early December), and the fruit are black with pulpy flesh that are mainly fed on by birds and some mammals including deer (Metcalfe, 2005). The flowers and fruit provide food between autumn and spring to a wide range of species, as previously discussed, making ivy a valuable species to support biodiversity over winter.

Figure 1.9 L-R: (a) *H. helix* 'Glacier' juvenile form and (b) *H. helix sp.* mature (arborescent) form (Photographs by Faye Thomsit-Ireland)

While both juvenile and mature types of *Hedera* grow leathery, evergreen leaves whose petioles lack stipules, the juvenile form has three to five triangular lobes whereas the mature phase has ovate to diamond-shaped leaves, possibly as a response to herbivory (Metcalfe, 2005). The two forms photosynthesise at different rates; mature leaves at 1.5 times the rate of juvenile leaves (Bauer and Bauer, 1980). Additionally, when young, many *Hedera* species leaves are covered in stellate or scale-like trichomes (McAllister and Marshall, 2017), which can potentially increase the particulate capturing quality of the plants (Chen et al., 2017).

Hedera are moderately to very drought tolerant depending on the species (McAllister and Marshall, 2017). Additionally, *H. helix* is tolerant to many forms of pollution including gaseous pollutants SO_2, NO_2, and O_3 (Steubing et al., 1989, Della Torre et al., 1998), and it can grow in soil types from pH 4 to chalk cliffs (Metcalfe, 2005). The mature leaves of *H. helix*, *H. hibernica* and potentially other *Hedera* species are tolerant to salt spray and some saline irrigation; however, there are cultivar differences in salt tolerance (Headley et al., 1992, Percival, 2005). *Hedera hibernica* grows above the tide line on shingle banks (Metcalfe, 2005), and can tolerate more extreme conditions than *H. helix,* such as growing in dry sunny areas and waterlogged ditches (McAllister and Rutherford, 1990).

Due to the ease with which *Hedera* grows in shaded conditions, if introduced to an area, ivy can be a highly prolific, invasive alien (Metcalfe, 2005). In the state of Oregon (USA) both *H. helix* and *H. hibernica* and all their cultivars are considered quarantinable noxious weeds which, if kept in a garden, must be prevented from spreading or seeding (Albert, 2010).

As *Hedera* species are generally shade, pollution, and moderately drought tolerant, they are an ideal choice for urban greening where pollutant concentrations can be higher, especially by roads. Additionally, *Hedera* can survive growing near buildings in the shade with restricted rooting and water availability caused by compacted soils and rain shadows (Rose, 1980, Morel et al., 2005).

1.4.2 Ivy management

In order to grow *Hedera* up a wall, the plants need to be situated as close to the surface as possible and leading shoots directed towards the wall. A small mesh wire or plastic trellis/netting can be used to press the plant against the substrate to encourage attachment (Dunnett and Kingsbury, 2008). Alternatively horseshoe-shaped galvanised staples or cable nails can be used to secure ivy to a wall in the early stages of growth (Rose, 1980). Irrigation or watering during establishment could be considered as buildings can produce rain shadows (Rose, 1980) and increase the surrounding air temperature through reflected and convected heat (Perini et al., 2011b), thus increasing evapotranspiration. Shading is necessary for ivy to produce adventitious roots, as sunlight inhibits their production (Negbi et al., 1982). Given that ivy grows in shade, it may be used as a bottom layer, with a different species of climber growing over the top, using ivy as the support (Rose, 1980). If ivy is grown against a building, the aspect of the wall must be considered regarding solar gain, sheltering, and wind tunnel effects.

Ivies on south facing walls tend to be more prone to pests, especially red spider mite (*Tetranychus urticae*; (Rose, 1980)). Other ivy pests including soft, peach, and oleander scales (*Coccus hesperidum*, *Parthenolecanium corni* and *Aspidiotus nerii*), are often noticed due to a build-up of sooty mildew on the leaves caused by the honeydew the scales produce. Additionally, scales can be problematic to car owners as the honeydew can form a sticky layer on car paintwork (Rose, 1980).

The impression provided by an exterior green façade is impacted by the colour and leaf shape of the *Hedera* species used. Large leaved species such as *H. colchica* and *H. canariensis* (only hardy in southern UK), work well with large houses, buildings (McAllister and Marshall, 2017), and potentially tower blocks. If the leaves are too large for the building, they can overwhelm the structure; mixing large and small leaves, adds contrast and increases the layers of insulation. Small-leaved varieties include *H. hibernica* 'Deltoidea' and *H. helix* 'Pedata' (a bird's foot ivy).

Colour combinations may provide variety; *H. helix* 'Cavendishii' and 'Buttercup' have pale cream-coloured leaves which contrast with redbrick walls, while the purple-leaved varieties such as *H. helix* 'Atropurpurea' and 'Glymii' work well with white or stone walls (Rose, 1980, Rose, 1996). For north facing walls, *H. nepalensis* grows well and blends with *Asters* (Michaelmas daisies), *Heleniums* or *Crocosmia* (Rose, 1980).

The wide range of species and cultivars, mean that multiple forms of ivy can be used, each matched to the requirements of the landscape or structure, from ground to building cover. To keep ivy neat around a building, pruning may be required in the late summer and/or spring, which also reduces the number of insects within the ivy (Rose, 1980). Some species such as *H. canaeriensis* only need clipping after frost damage, which is not the case for *H. colchica* or *H. nepalensis*, which may need pruning with secateurs if they have overgrown the structure (Rose, 1980).

The ease with which ivy grows and the minimal support it requires make *Hedera* species a potentially inexpensive form of amenity planting in urban estates, though maintenance and pruning would be required.

1.4.3 Adhesive mechanisms of *Hedera* roots and adhesion to different material types

There are two types of roots in *Hedera* species, 'true' and 'adventitious'; 'true' roots absorb nutrients and anchor the plant to the ground, thus providing stability (Figure 1.10a), and adventitious aerial roots are used for attachment while climbing (Figure 1.10b and c; Melzer et al. (2010)). Both types of roots have common features; these include a root cap which protects undifferentiated (meristematic) cells from the substrate, and root hairs (Ridge and Katsumi, 2002). Juvenile cuttings form roots more easily than mature cuttings (Girouard, 1967a, b), which may be due to the absence of phloem lignin in juvenile cuttings (Reineke et al., 2002), and the number of roots formed is dependent on the length of exposure to rooting hormone (Geneve et al., 1990). The aerial roots are typically between 1 mm and several centimetres long and are covered in root hairs (Figure 1.10c), which exude attachment adhesive (Melzer et al., 2010).

Figure 1.10 L-R: (a) Adventitious 'true' roots induced via rooting hormone (auxin), (b) aerial roots growing from the *Hedera* stem, (c) aerial root 100x magnification with visible root hairs (Photographs by Faye Thomsit-Ireland)

1.4.3.1 Adhesive mechanisms of *Hedera*

Several studies have investigated aerial root attachment in *Hedera* (Zhang et al., 2008, Wu et al., 2010, Xia et al., 2010). Attachment is initially triggered by contact between the aerial root tip and another surface (Melzer et al., 2009, Melzer et al., 2010, Lenaghan and Zhang, 2012), which increases the number of aerial roots as well as their growth rate. The aerial roots align with the substrate to which they are adhering, then grow to varying lengths and widths to maximise contact with the substrate. As they align, a yellow adhesive substance is secreted, which forms droplets on the ends of the root hairs and can start curing on contact with the substrate (Lenaghan and Zhang, 2012). As adhesive secretion initiates the root hair cuticle degrades; the secretion process lasts 4-6 hours (Lenaghan and Zhang, 2012). Once the adventitious roots contact the substrate they start to dry-out, and deform, and twist, this process locks them into the wall substrate, providing a strong, binding force (Melzer et al., 2009).

The secretion of *H. helix* contains uniform nanoparticles (Zhang et al., 2008). These nanoparticles consist of 19 organic compounds, which have a polar 'head' and a hydrophobic 'tail', indicating that the force holding the aerial roots to the surface is a combination of hydrogen bonding and weak adhesive force (Zhang et al., 2008). Results of a modelling study showed that the binding strength of ivy attachment can be attributed to van der Waals forces and cross-linking of nanoparticles in the adhesive secretion with the substrate (Wu et al., 2010, Lenaghan and Zhang, 2012).

1.4.4 Aerial root attachment to various building materials

While *Hedera* appears to climb over many materials with ease, it does not always attach with aerial roots, sometimes twining round a support if the surface is not a suitable substrate (personal observation, 2013). For ivy and other self-attaching plants, the aerial roots require a suitable texture for attachment, such as bark, rock, brick, render or cement, the rougher the better (Dunnett and Kingsbury, 2008). Smooth, reflective surfaces, such as metal and glass are unsuitable, as is soft brick/ mortar where roots can penetrate more deeply and cause damage (Dunnett and Kingsbury, 2008).

The material properties and whether or not they promote *Hedera* attachment was explored by Melzer et al. (2010). Biomechanical failure in the ivy adhesion occurs after the build-up of several smaller failures, finally leading to complete failure (Melzer et al., 2009). In tests where ivy was attached to mortar (type not stipulated) the majority of adhesive failures occurred due to substrate failure (70 in 74), whereas for ivy attached to cork, adhesive failures were a combination of root, stem, and substrate failures (Melzer et al., 2012). Melzer (2012) showed that where both the substrate and adhesion is strong (resistant), the stem becomes the next weakest area.

Based on Melzer et al.'s (2009 and 2010) lists and additional observations of *Hedera* aerial root behaviour, material properties that increase the likelihood of ivy attachment are surface pore size (where the deformed aerial roots can physically attach) and/or chemical composition for bonding with the adhesive. *Hedera* appears likely to attach to materials with a surface pore size greater than 4 µm; however, as maximum pore size for bricks and concrete can range from 0.12-40 µm (Straube, 1999), and ivy can be found attaching to many brick types, the mean surface roughness (Ra) may be a better measurement to predict whether ivy will attach to a surface. Ra describes the mean depth of pits in the surface; for brick the Ra is between 12 µm and 27 µm depending on weathering. Polished marble is around 0.74 µm but may increase to around 29 µm after cleaning with glass shot (sandblasting) and limestone and sandstone range from 17-61 µm, depending on treatment (Charola et al., 1996, Grissom et al., 2000). If *Hedera* is assumed to attach to surfaces with an Ra of greater than 4 µm, as per the indication of pore size, ivy is likely to attach to brick, limestone, sandstone, and unlikely to attach to polished marble. If, however, marble is sand blasted, ivy may be able to attach, though this was not tested. Alternatively, if pore size is less than 4 µm and the chemical composition of the material is suitable, it may be able to attach chemically through adhesive secretion, as was reported regarding mylar foil (Table 1.3).

Table 1.3 Summary of material properties and ivy (*H. helix)* attachment to various material types (from Melzer et al., 2009)

Material	Organic/Inorganic	Pore Size (µm)	Adhesion
Aluminium	Inorganic - metallic	0.37	N
Steel	Inorganic - metallic	0.39	N
Glass	Inorganic	0.01	N
Ceramic	Inorganic	0.08	N
PVC	Inorganic - polymer	0.25	N
Plexiglas	Inorganic - polymer	0.53	N
Beech Wood	Organic	9.47	Y
Construction Paper	Organic	6.40	Y
Cork	Organic	13.46	Y
Spruce Wood	Organic	4.43	Y
Mylar Foil	Inorganic - polymer	0.25	Y
Sponge Rubber	Inorganic - polymer	4.95	Y

1.4.4.1 Renders and mortars

Renders on buildings are typically made from a mixture of ingredients including lime, cement, and acrylic. While results from a study by Sternberg et al. (2010a) on limestone and lime mortar walls regarding *Hedera* aerial root damage are still awaited, ivy may penetrate cracks in render and drive it from the wall, or cause water to enter and 'blow' the render (Sternberg et al., 2010a, Henry & Stewart, 2011). Therefore, where cracks in the render have been observed, *Hedera* should be avoided, and a support system (such as a trellis) for the ivy to grow on may be beneficial even on good quality render (personal observation).

Conversely, Portland cement, when used as a constituent in mortar or concrete, which has been the case preferentially over lime since 1930s (Marshall and Dann, 2013), forms a stronger mortar that is less vulnerable to penetration from *Hedera* aerial roots (personal observation).

1.4.4.2 Metal surfaces

Metals such as steel and aluminium have been found to inhibit *Hedera* aerial root attachment (Melzer et al., 2009). This may be due to a number of factors, including reflectiveness and Ra.

Pre-constructed *Hedera* screens use a number of species and cultivars including *Hedera x soroksarensis* 'Woerneri', which are hand-wound on a trellis of galvanised steel (zinc-coated steel) (McAllister and Marshall, 2017, Mobilane UK Ltd., 2018b). The *Hedera* does not attach to the frame, but only onto other ivy stems (personal observation, 2013). Furthermore, on sheets of galvanised steel *H. helix* tends to cover the surface without forming an attachment, allowing the ivy to be easily lifted (personal observation, 2013). Given that the Ra of steel ranges from 0.1 µm to 7.5 µm depending on the manufacturing technique and finish (Euro Inox, 2014), it is unlikely that this factor alone inhibits ivy aerial root attachment.

Alternatively, aerial root attachment failure may be due to metal phytotoxicity. Metal phytotoxicity causes damage, restricted growth, and ultimately 'true' root and plant death. Phytotoxic metals tend to affect the roots first, so the plant may not initially show any signs of ill health (Ernst, 1996). Typically, it is free metals ions in salt solutions that are phytotoxic (Wheeler et al., 1993, Kopittke et al., 2010), which is why metal salts (such as copper hydroxide and zinc carbonate basic) can be used in root pruning (Beeson Jr and Newton, 1992, Baker et al., 1995). Aerial root growth, specifically, has been shown to be restricted by metal salts containing copper and lead (Liu et al., 2012).

Practically, copper meshes and sheets have been used to prevent seedling roots matting when growing in tubes (Saul, 1968, Barnett and McGilvray, 1974). Additionally, copper mesh has been found to restrict tree roots and girdle those that penetrated the openings (Wagar and Barker, 1993). While sheet metals such as galvanised steel are anecdotally recommended as root barriers when inserted into the ground, there is no research to show whether sheet metal has phytotoxic effects.

Lastly, it has been observed that highly reflective surfaces (even from bright paint) can deter self-attaching climbing plants such as *Hedera* (Dunnett and Kingsbury, 2008). This may be because light inhibits *Hedera* aerial root production (Negbi et al., 1982) and self-attaching mechanisms in plants such as aerial roots and suckers are negatively phototropic; they seek darkness (Dunnett and Kingsbury, 2008).

1.4.4.3 Anti-graffiti paints

Anti-graffiti paints are considered here because of their potential role in preventing *Hedera* aerial root adhesion to walls. Anti-graffiti paints come in two main forms, sacrificial and permanent (Whitford, 1992, Lyons, 2010).

Sacrificial coatings are designed to be removed with jet washing when graffiti is removed from walls (Lyons, 2010). While not previously tested as *Hedera* repellent, sacrificial coatings may work in a similar way to whitewash or lime wash (personal observation). These paints have a powdery finish to which *Hedera* does not easily attach, as the sacrificial surface does not adhere to the substrate beneath (Dunnett and Kingsbury, 2008).

The permanent paints, however, are more convenient and may prevent *Hedera* adhering or growing aerial roots. There are several types of permanent anti-graffiti paints including formulations based on polyurethane and those using nanoparticles such as fluoroalkylsilanes or silanes (Lyons, 2010). Polyurethane based anti-graffiti paint reduces the surface roughness and has a high density of crosslinks (Liu et al., 2013) that could inhibit *Hedera* adhesion entirely by preventing the adhesive from forming cross-links with the paint (personal comment). More recent nanoparticle-based formulations repel water, oils, and algal/fungal build-up (Weißenbach and Standke, 2001, Weißenbach et al., 2008, Arkles et al., 2009, Urban Hygiene Ltd., 2014), thus reducing the chance of substrate development. While the silane-based anti-graffiti paints require testing, they may prove suitable for preventing aerial root adhesion as the silanes may interact at the same spatial scale as the nanoparticles in the *Hedera* adhesive.

1.4.5 Impact of abiotic stresses on *Hedera*

1.4.5.1 Water deficit

Water forms 80-95% (by weight) of most growing plant tissues, and on a hot, sunny day a leaf can exchange 100% of its water in an hour (Taiz and Zeiger, 1998). Evapotranspiration occurs when water evaporates, primarily from leaves (via the stomatal pathway), thus reducing the temperature of the plant (Taiz and Zeiger, 1998). The growth rate of plant cells is proportional to the cell turgor, therefore, decreasing water availability reduces the cell turgor, and thus plant growth. Hence, water deficit is identified through reduced height (stunting) and lower leaf numbers. During the early stages of water deficit, the photosynthetic rate tends to remain unchanged, so energy that is no longer generating leaf area (due to reduced cell turgor) is diverted to increase root volume in search of water. This effect is greater for plants in a vegetative phase rather than in a reproductive phase, as reproduction tends to be prioritised over root growth. An initial response to water deficit is reduced leaf stomatal conductance; stomata are closed to protect the plant against desiccation and reduce evapotranspiration (Taiz and Zeiger, 1998). Stomatal closure during periods of water deficit resulting from a loss of turgor in the guard cells can be triggered hormonally via abscisic acid (Sauter et al., 2002) or directly through water loss (Taiz and Zeiger, 1998).

Over longer periods, leaves adapt to water deficit with increased cuticular wax and pubescence. These features reduce water loss to evaporation and increase reflection (Taiz and Zeiger, 1998). The waxy leaves on ivy indicate that it is drought tolerant and while most *Hedera* species are fairly drought tolerant; *Hedera maroccana* (Moroccan ivy), the tetraploid *H. helix* (from Sicily), *H. canariensis*, and *H. algeriensis* are very drought tolerant (McAllister and Marshall, 2017). While the drought resistance of *Hedera* may be useful when growing next to buildings or in compacted urban soils, the growth retarding results of water deficit may offer a mechanism to manage ivy growth.

1.4.5.2 Root restriction

The effects of root restriction on plant growth are evident in both traditional and hydroponic systems, even where water and nutrient supplies are adequate (Kharkina et al., 1999). The effects of root restriction (through growing plants in small and growth-limiting planting holes or containers) include reduced plant height, leaf number, and photosynthetic rates (Richards and Rowe, 1977, Herold and McNeil, 1979, Ismail and Davies, 1998).

The reduced photosynthetic rates of root-restricted plants are thought to be, in part due to a lack of nutrient and water availability. Additional stresses from unfavourable rooting conditions at the edge of containment, where the greatest temperature fluctuations are experienced, cause further reductions (Poorter et al., 2012). Additionally, reduced concentrations of oxygen at the root level, occurring as a consequence of root restriction, along with reductions in root respiration, may also affect plant growth (Kharkina et al., 1999).

As root restriction reduces plant and root growth, it may also reduce aerial root production in *Hedera*, therefore providing another viable option for management of ivy attachment and growth.

1.5 Computational modelling of buildings and plant interactions

Computer modelling is used to study systems that are too complicated to represent manually, such as the annual internal temperature of a building and heat flux dynamics due to different construction materials. Modelling plant impacts on buildings is complex as there are multiple components and interactions, which affect the temperature (internal and external) of a building. Plants around buildings provide shade (McPherson et al., 1988, Papadakis et al., 2001, Ip et al., 2010, Pérez et al., 2011a), cooling through evapotranspiration (Takakura et al., 2000, Pérez et al., 2011b, Malys et al., 2014, Scarpa et al., 2014), insulation (Bolton et al., 2014, Cameron et al., 2015), and reduce wind velocity (DeWalle and Heisler, 1983, Perini et al., 2011a). Furthermore, the interaction between plants and structures is dependent on building construction, maximum insulation depth, climate, season, and local weather conditions (Ottelé et al., 2011, Olivieri et al., 2017).

Examples of early simulations modelled the effects of tree shading and wind inhibition on building heating and cooling requirements, which produced up to a 93% correlation with experimental data (Huang et al., 1987, 1990). Increased computational power meant that more complex systems could be simulated, which incorporated the effects of plants and trees on air flow in 'street canyons' (Bruse and Fleer, 1998).

There have been many simulations on the impact of tree shading on building energy consumption, both at the building and larger scales, across many climates, and incorporating many structural variables (Simpson, 2002, He et al., 2009, Nikoofard et al., 2011, Wong et al., 2011, Ng et al., 2012, Pan and Xiao, 2014, Djedjig et al., 2015, Musy et al., 2015, Skelhorn et al., 2016).

Despite the inclusion of evapotranspiration in some early simulations (Huang et al., 1990, Takakura et al., 2000), its cooling effect was frequently excluded in later models (Kontoleon and Eumorfopoulou, 2010, Susorova et al., 2013, Scarpa et al., 2014). Additionally, some of the simulations did not utilise any experimental or field-based data to validate the accuracy of the model as they were purely theoretical studies (Bruse and Fleer, 1998, Alexandri and Jones, 2008, Wong et al., 2009). Nevertheless, predictions of energy savings resulting from urban greening based on simulations have been made for many countries including Canada, Japan, and the USA (Akbari and Konopacki, 2005, He et al., 2009, Nikoofard et al., 2011). When trees were simulated to shade residences in various states in the USA, the greatest predicted annual energy savings (372 kWh/93 m^2) occurred in areas with more than 3,500 but less than 4,000 cooling degree days, which were heated with gas and had residences built before 1980 (Akbari and Konopacki, 2005). In Vancouver, Canada, a simulation of trees planted to shade the west side of a building showed a reduction of overall heating-cooling energy requirements by 1.53 GJ annually (Nikoofard et al., 2011). When a two-storey house surrounded by buildings in Tokyo, Japan, was simulated, the addition of bushes/trees, 1-2 m away from all four sides of the building, reduced cooling loads by between 4.3% and 25.1%, depending on the height of the trees (He et al., 2009). Some validated heat transfer models of living wall systems included cooling by plants via evapotranspiration; one study used inputs for heat flux parameters with an adapted version of the Penman-Monteith equation, and produced results that were within 1 ^{o}C of the leaf and substrate temperature of the plants in the living wall (Malys et al., 2014).

A wide range of modelling tools and applications have been used to model green walls and vertical greening systems (occasionally over windows) including Envi-met (Bruse and Fleer, 1998), Visual DOE 2.1 (Huang et al., 1987, Akbari and Konopacki, 2005), C++ (Alexandri and Jones, 2008), TAS (Wong et al., 2009), EnergyPlus (Larsen et al., 2014), and IES (Laparé, 2013). Each of these modelling tools offers both advantages and disadvantages. However, one of the main advantages of IES software is the user-friendly interface, which includes a drawing package for easy generation of buildings (Model-IT), an in-depth energy modelling package (Apache), and a sun path simulation that contributes to calculating the solar gains at the external surfaces and hence improves internal temperature predictions (SunCast).

Only one other study has performed a simulation of the movement of heat, air, and moisture with a green wall using IES software; the green wall was modelled as an additional room attached to the outer wall with an HVAC (heating ventilation and air conditioning) system to represent the plants' evapotranspiration processes (Laparé, 2013). Other studies have modelled green walls using IES software, but without explanation of methodology (Tachouali and Taleb, 2015), or by modelling modular living wall components without including plants and hence without the cooling influence due to evapotranspiration or shading (Alabadla, 2013).

IES software was therefore chosen to model direct greening, as it is user-friendly, inexpensive for research use, often utilised commercially, and has previously shown its suitability for the task.

1.6 Current Building Regulations

Currently, the UK government is aiming to meet an 80% reduction from 1990 CO_2 emissions by 2050. To achieve this, between 400,000 and 1.8 million houses per year need upgrading to reduce energy use (The Stationery Office, 2010b).

The Building (Scotland) Act (1959) laid out the first national legislative framework allowing local authorities to specify minimum building standards from which the Building Regulations (1964) were commissioned (Manco, 2009). This Scottish act was followed by a national Building Control Act (1966), which established building control authorities covering England, Scotland and Wales, Northern Ireland (in 1972), and the Republic of Ireland (1990). This act was updated in England and Wales in 1984, and in Scotland in 2003 (Manco, 2009).

Regulations relating to the thermal properties of buildings (Part L of the Building Regulations (Conservation of fuel and power)), came into force in 1995 (Kerr, 2012), being revised in 2002 for residential and non-residential buildings. In 2006 and 2010 respectively, a 20% and 45% reduction in CO_2 emissions (compared to 2002 levels from energy savings in space heating, hot water, and lighting), was required in new residential properties (Kerr, 2012). From 2013, new builds were required to reduce CO_2 emissions (relating to building use and operation), by a further 8-26% (Kerr, 2012). Unfortunately, the necessity for new builds across England to be ‘zero carbon’ or ‘carbon neutral’ was removed in 2015 by the government, though this remains a requirement in London (Ares, 2016). No embodied or appliance based CO_2 emissions are currently included in the building regulations (Kerr, 2012).

Reducing thermal transmittance (U-value) of the building fabric reduces the energy required to heat a structure, as less thermal energy is lost through the building envelope. This has already impacted the U-values of materials required to meet building regulations (Table 1.4). Ivy cladding could have a role for future builds as it can reduce the U-value of walls (section 1.2.1), and may offer a cheaper method of meeting regulations. However, plant-based solutions alone cannot improve the insulation of a building to current standards, therefore the use of traditional insulation methods are required as well (Perini, 2013).

Table 1.4 U-values changing with updated Building Regulations (Kerr, 2012)

Element	2006	2010	2013
Roof	0.25	0.2	0.16
External Wall	0.35	0.3	0.2

There is currently no relevant legislation relating directly to *Hedera*. Plants must, however, be maintained and not be allowed to become a nuisance, as any damage by plants to people or property may result in a civil suit for nuisance or criminal prosecution under the Occupiers' Liability Act 1957 (Figure 1.11; Royal Horticultural Society (2018c)).

Figure 1.11 *Hedera* collapsed from fence (Photographs by Faye Thomsit-Ireland)

1.7 Policies, barriers and drivers influencing green wall uptake

To overcome barriers to green wall installation, it is important to understand the drivers and local policies already in effect that both positively and negatively affect local perceptions to green wall installation, along with the environmental and economic sustainability of green walls.

Within the UK, several policies encourage the use of green walls, though there are currently no mandatory requirements for their installation or maintenance. These consist of a mixture of statutory and non-statutory policies derived from the National Planning Policy Framework, including local targets on greening such as the All London Green Grid, which feed into Local Plans (Department for Communities and Local Government, 2012, GLA, 2012). Occasionally local authorities mandate greening; however, resulting installations are rarely monitored for quality (Natural England, 2015).

1.7.1 Barriers to implementation and incentives for green walls

While building greening has been implemented for centuries, from the turf houses in Iceland to sod roofs in Germany (Köhler, 2006, Noble, 2007, Dover, 2015), it has been, until now, primarily associated with the need to insulate built structures cheaply. While the driving forces and barriers for the uptake of green walls have not been formally assessed, Table 1.5 is a summary based on reviewed pros, cons, and relevant barriers to green roof installation (Peck et al., 1999, Köhler, 2008). Furthermore, these driving forces and barriers operate at multiple levels ranging from the individual to the area strategic level; each city and country will have a different mixture of them influencing green wall uptake.

Table 1.5 Summary of the forces driving the uptake of green walls and the barriers to that change, for different wall types, GF = green façades, namely direct and indirect greening, DG = direct greening, LWS = living wall systems. Based on BRE et al. (1996), Peck et al. (1999), Köhler (2008), Williams et al. (2010), Hopkins and Goodwin (2011), Irga et al. (2017)

Driving forces	Barriers
Improving the climate of the local area by reducing UHIE (GF, LWS)	Gutter or standpipe obstruction (GF) and risk of damp (DG)
Improving local air quality (GF, LWS)	Lack of knowledge (GF, LWS)
Increasing biodiversity (GF, LWS)	Increased pests (GF)
Creating green corridors and habitats through cities (GF, LWS)	Daylight reduction in rooms (GF, LWS)
Improved aesthetics (GF, LWS)	Building damage (GF)
Improving the mental well-being and feelings of the local residents (GF, LWS)	Lack of demonstration projects for inspiration and confidence (GF, LWS)
Joining green corridors without using additional space (GF, LWS)	Lack of standards, therefore cannot guarantee quality of the product (LWS)
Novelty (LWS)	Additional costs (GF, LWS)
Aesthetics (GF, LWS)	Maintenance (GF, LWS)
Public health (GF, LWS)	Problems with building restoration (GF)
Energy savings through increasing the thermal resistance of the building façade	Lack of relevant and reliable local research in the economic and environmental benefits (GF, LWS)
Reducing surface water runoff (GF, LWS)	High costs, and inexperienced installers (LWS)

1.7.2 Green walls' environmental and economic sustainability

Green walls are considered to be a part of sustainable building solutions (Manso and Castro-Gomes, 2015), however, their sustainability requires quantification. This can be performed with a procedure called life cycle assessment (LCA). LCA evolved from assessments of the environmental impact of a product 'from cradle-to-grave' (Hunt and Franklin, 1974). LCA is divided into four stages; scoping, inventory, eco-profiling, and interpretation (Ayres, 1995). During the scoping phase, the system to be considered is defined, including the functional unit (which is the part of the system to which the inputs and outputs refer, for example, 1 m^2 of green wall), as are relevant impact categories such as global warming, human and eco-toxicity, resource depletion, and eutrophication (Ottelé et al., 2011, Curran, 2013). In 1998, an international standard ISO 14041 was developed for LCA which was updated in 2006 by ISO 14040 and ISO 14044 (ISO, 2006b, ISO, 2006a), with no further updates since. Criticisms of LCA have been noted, which include concerns about how energy costs and environmental implications are calculated (Ayres, 1995). LCAs often include simulations of the benefits derived from green wall usage (Ottelé et al., 2011, Pan and Chu, 2016). These have shown that direct and indirect greening (for example, with *Hedera*), are environmentally sustainable in temperate climates such as the UK (Ottelé et al., 2011).

Another method, cost-benefit analysis (CBA), can be used to assess whether the long term benefits of an action outweigh its upfront capital costs. There are many methods of calculating benefits, both in terms of private advantages (to the individual or company who for example, installs a green wall) and public good (such as increased biodiversity and better air quality). Both the public and private benefits must be considered when conducting a CBA to assess incentivisation strategies (Claus and Rousseau, 2012). A private CBA can be used to decide the necessary incentive value that would overcome increased capital costs (especially where the private benefits are marginal or insufficient). Additionally, the public CBA assesses whether the costs of an incentive scheme are outweighed by the value of the potential public good (Claus and Rousseau, 2012). CBA could be utilised to determine whether the benefits of installing green walls or ivy cladding outweigh the costs involved in installation and maintenance. If those benefits are marginal, CBA can then be used to assess the financial incentives that would make green wall installation viable.

1.8 Aim, objectives, and scope of the research

Green walls, whether as direct/indirect greening or living wall systems, provide many environmental benefits (see section 1.1.1). Green walls are already part of urban greening and ecosystem service provisioning in cities (section 1.2), therefore it is important to investigate barriers surrounding the use of climbing plants as part of direct greening (section 1.3). The aim of this thesis is to mitigate these obstacles and provide scientific evidence for appropriate direct greening.

The objectives of this thesis are:

1. To investigate year-round thermal and RH impacts of direct greening, using model brick ‘buildings’ as a case study with particular focus on *Hedera* and some alternatives;

2. To produce a computational model of the impact of *Hedera* cladding on internal temperature in summer and winter for the above model brick 'buildings';

3. To investigate possible techniques of controlling and preventing unwanted ivy attachment;

4. To explore policy mechanisms aimed at increasing implementation of green walls and, in particular, green façades.

1.8.1 Experimental investigation of thermal and RH impacts of direct greening

While there is ample literature on the cooling benefits of green walls in summer (Hoyano, 1988, Ip et al., 2004, Pérez et al., 2011a, Cameron et al., 2014, Ottelé and Perini, 2017), much less covers benefits derived in winter (Sternberg et al., 2011a, Bolton et al., 2014, Cameron et al., 2015). Additionally, a simulation indicated that if green walls are installed on an inappropriate aspect (for example, the south façade); they block solar gains in winter, thus increasing space heating requirements (Carlos, 2015).

This study investigates the impact of climbing plants on the changes in temperature and relative humidity (RH) around the building envelope. Brick cuboids are used to represent buildings, as this provides replication and the opportunity to study different plant species (Chapter 3).

This study will add to the wealth of research on the cooling effects of green walls on buildings in summer, while incorporating less frequently researched factors such as the impact of vegetation on relative humidity on/within a built structure and the stabilising effects of green walls on the building envelope microclimate. The study will also consider the effects direct greening in winter, both with and without internal heating, which builds on other winter studies (Sternberg et al., 2011a, Bolton et al., 2014, Cameron et al., 2015, Ottelé and Perini, 2017). Finally, this study aims to deduce whether concerns regarding climbing plants increasing building RH are appropriate or misinformed, and if the latter, to generate interest with a view to changing opinions.

1.8.2 Computational modelling

If green walls can be integrated into building developments at the design phase, fewer construction materials are required, thus improving the cost effectiveness of green walls. Additionally, retrofitting with direct and indirect greening adds minimal additional costs as compared to LWS (which are best added during initial construction) and can typically be retrofitted as long as the walls can sustain a supporting structure.

In both cases it would be advantageous to model effects and relevant structural considerations prior to installation. However, to model the potential benefits of green walls and to avoid adverse conditions, accurate green wall layers must be generated in commercially available building energy analysis software, as green walls influence the internal building conditions. Integrated Environmental Solutions (IES) software was chosen for the project as it does not currently offer a suitable model for a plant-based layer in the system.

This project aims to create a validated green façade model for IES (Chapter 4), that could be used commercially and therefore could encourage the design of buildings with integrated green walls. This model will be based on the brick cuboids (model 'buildings') used experimentally in Chapter 3 as they are simple (with no windows or additional heat gains) and therefore represent an ideal base from which to develop a model. The model simulation will be validated against year-round data from experimental brick cuboids with and without plant covering, with the objective of generating a suitable representation of a plant layer that can be applied throughout the year.

1.8.3 Investigation of *Hedera* management solutions

Hedera and other self-attaching plants may be found across the country, on domestic dwellings and other walls where it may have established naturally, however, maintenance remains one of the top concerns for those using greened walls (Köhler 2008). Reducing the maintenance requirements of self-attaching climbing plants could remove some of the barriers to installation and maintaining established green façades. The attachment process for ivy aerial roots was extensively investigated by Melzer et al. (2009) who observed that they align with the attachment substrate, then deform and secrete an adhesive substance to secure the plant in place. The composition of the adhesive substance was found to contain uniform nanoparticles (Zhang et al., 2008) leading to the idea that *Hedera* may be managed though nanoparticle based anti-graffiti paint, alongside other materials. Additionally, literature on root restriction and water deficit indicates that plants are commonly stunted under these conditions (Taiz and Zeiger, 1998) and aerial root growth may also be impeded (Stevenson and Laidlaw, 1985). This provides another management method for controlling ivy as it grows up buildings.

This project endeavours to find effective management solutions for direct greening especially using *Hedera*, in order to reduce concerns regarding its use. Two methods will be investigated: reducing attachment through the use of paints and metal sheets/meshes on the building envelope, and plant manipulation through root restriction and water deficit (Chapters 5 and 6).

1.8.4 Exploration of policy and incentives

Over the course of this study, the green wall industry in the UK has expanded dramatically and gained in experience. The policies and drivers for the uptake of green wall installation have also changed with different governments; the Code for Sustainable homes has been abolished, but an overall vision for greener cities remains. Therefore, this final section (Chapter 7) aims to summarise some of the remaining barriers to green wall installation and explore them within the context of the UK. Chapter 7 covers a diverse range of topics in an attempt to further explore the barriers to green wall adoption; it aims to review the overall health and target markets of the green wall installation industry in the UK using case studies from major green wall installers.

As green walls can be used as a symbol of sustainable building practises, the sustainability of green walls and companies which install them are considered using LCA. To examine the economic viability of green walls a CBA from literature is considered; however, as they offer benefits in multiple areas, but no single large benefit, the monetisation of green walls is also deliberated upon. This study also aims to investigate the funding streams available for green wall installation and maintenance, as some systems (especially LWS) can be very expensive. As the barriers and incentives for installing green walls have not been explicitly studied in the UK, global examples and other greening forms were used to draw analogies to the local situation. The objective of this research is to gauge the current position of the UK industry along with existing/possible incentives and planning policies.

1.8.5 Scope of the research

While many climbing plants can be used for both direct and indirect greening, this study primarily focuses on *Hedera*, as it is a plant whose reception is mixed, yet it is commonly used (particularly in a domestic settings and with older housing stock) and much studied. This said, two further species, a deciduous self-attaching climber (*Parthenocissus tricuspidata*) and another evergreen self-attaching climber (*Pileostegia viburnoides,* climbing hydrangea) were considered for study due to their frequent use in landscaping projects (R. Griffin, personal comment), though it was ultimately decided that it was beyond the scope of this project to investigate more species. Additionally, neither *Parthenocissus* nor *Pileostegia* have the same poor reputation regarding climbing or attachment vigour as *Hedera*.

Direct greening presents fewer financial barriers (compared to living wall systems) therefore displays more potential for rapid uptake if some basic barriers are overcome. Since widespread greening is the aim, indirect greening and living walls are mostly considered outside the scope of this thesis. Additionally, and for the same reasons, residential buildings were primarily considered, rather than commercial buildings. The work in this thesis focuses on the UK where experiments were performed and there was familiarity with local policy; while some of results could be applied in similar situations globally, global impacts have not been considered.

Chapter Two

Research methods

2.1 Introduction

Within this chapter, methodology for the experimental procedures is presented, along with explanations of sensors, sites, and general methods used.

Two main groups of experiments were conducted. One group (experiments 1 and 2) centred on understanding the impact of direct greening on building temperature and humidity. The other group (experiments 3 and 4) focussed on a narrower question of which tools and techniques could ease *Hedera* management by mitigating its adhesion to surfaces.

The first experiments measured the impact of various plant species, when grown around wall surfaces, on the temperature and relative humidity (RH) of model 'buildings'.

For the first year's summer experiment, pre-existing unmortared model 'buildings' were used (experiment 1). The model 'buildings' were mortared and additional insulation installed, in the 2nd year of the project, before the first winter experiment (experiment 2). Details of building upgrades and sensor layouts are provided in sections 2.6-2.8.

The literature review indicated that metals and anti-graffiti paints potentially contained suitable properties for inhibiting the attachment of ivy aerial roots. A laboratory-based model system for cutting attachment was developed to enable replicated studies of plant attachment to a range of surfaces. Treatments that reduced or inhibited ivy aerial root attachment in the model system were then field-tested on established ivy *in situ* (experiment 3).

Furthermore, root restriction and drought stress have been reported to reduce the height and number of leaves in plants (Richards and Rowe, 1977, Ismail and Davies, 1998). Therefore, the effect of water deficiency and container size on plant growth and aerial root production in *H. hibernica* plants (a fast growing species) was investigated (experiment 4) with two container sizes (275 mL and 2 L) and two watering regimes (well-watered and stressed, substrate moisture content (SMC) > 0.25 m^3m^{-3} and < 0.15 m^3m^{-3} respectively; Blanuša et al. (2013)).

Additionally, model 'buildings' were simulated using the building analysis software Integrated Environmental Solutions; IES (IES VE 2017.1.0.0, IES, Glasgow, UK). The model was developed with information derived from the literature and *in situ* measurements on the model 'buildings' (see

Chapter 3) which was used to provide the initial conditions. Inputs were then varied in order to modify the trends towards a better resemblance of results gained from the physical model 'buildings' (experiments 1 and 2). Full details of model development, inputs used in the simulations, simulation results and further model adaptions are provided in Chapter 4.2.

2.2 Location of the experiments and monitoring of the environmental conditions during experiments

Experiments 1, 2 and 3ii were conducted outdoors, within the field and glasshouse complex of the School of Agriculture, Policy and Development at the University of Reading (UoR) to simulate conditions in a dynamic 'real life' environmental setting. Data on local meteorological conditions were obtained from the nearby UoR Meteorological Observatory (UoR MO). Wind speed at 10 m and precipitation at the experimental site were assumed to be similar to the values recorded by the UoR MO. When in summer 2014 (during experiment 1), the UoR MO failed to record measurements, data from the High Wycombe MO was used to approximate ambient temperatures and RH (the RH was estimated from the wet and dry bulb temperatures), as this station was the nearest one with a fully accessible data set. Measurements of mean ambient conditions during the experimental periods for experiments 1 and 2 are included in the results sections of Chapter 3.

Experiments involving cuttings (experiment 3i) were conducted indoors, in a laboratory setting, as pilot studies indicated that when cuttings were kept in glasshouse conditions, the water in the test tubes became very warm (> 40 ^{o}C for a considerable part of the day) and cuttings' growth was inhibited. Mean daytime light levels in the laboratory, in the vicinity of the plants during the experiment, were 400 µmol m^{-2} s^{-1} (measured with a pyranometer SKS 1110: Skye Instruments Ltd, Llandrindod Wells, UK). Mean daily temperatures in the laboratory over the course of the experiment, in the vicinity of the plants, were 20 ^{o}C (minimum 16 ^{o}C, maximum 27 ^{o}C) and the mean daily RH was 60% (minimum 40%, maximum 80%); temperature and RH measurements were made every 30 minutes by a TinyTag ® logger Plus 2 – TGP – 4500 (Gemini Data loggers Ltd, Chichester, UK). Temperature measurements made with a TinyTag ® were accurate to 0.5 ^{o}C and the RH was accurate to 3%.

Experiment 4 was primarily conducted in a temperature-controlled, unshaded, UoR glasshouse. The glasshouse was ventilated when temperature rose above 21 ^{o}C to minimise interference of precipitation and overheating. Air temperature was recorded hourly with a Tinytag® logger Plus 2 – TGP – 4500. Over the experimental period the mean daily temperature was 16 ^{o}C (minimum 13^{o}C, maximum 22 ^{o}C) and the mean daily RH was 85% (minimum 50%, maximum 100%).

2.3 Plant material

Several self-attaching plant species were examined over the course of the project, including three evergreen species (*Hedera helix*, *H. hibernica* and *Pileostegia viburnoides*) and a deciduous species (*Parthenocissus tricuspidata*; Figure 2.1). *Hedera helix*, which was already established on the experimental site and is a species found growing extensively on buildings across the UK, was used in experiments 1, 2, and 3. Within the literature *H. hibernica* was noted to be a vigorous fast growing species, so was chosen for experiments 3 and 4. *Parthenocissus tricuspidata* is another common self-attaching deciduous climber (used both in the UK and abroad) and lastly, *Pileostegia viburnoides* is an alternative evergreen species, frequently used in landscape and garden design (R. Griffin, personal comment), both of these species were used in experiments 1 and 2.

Hedera helix | *Hedera helix* 'Glacier' | *Hedera hibernica* | *Pileostegia viburnoides* | *Parthenocissus tricuspidata* 'Veitchii'

Figure 2.1 Images of the plant varieties used experimentally (Photographs by Faye Thomsit-Ireland)

The plant varieties used around the model 'buildings' (experiment 1 and 2) were three-year-old *Pileostegia viburnoides* and *Parthenocissus tricuspidata* 'Veitchii' (obtained from Chiltern Trees and Shrubs, Wallingford, UK and Provender Nurseries Ltd, Swanley, UK, respectively) in 2 L containers. These were planted around the model 'buildings' at the end of April 2014. Eight plants were installed around each 'building', two per side, spaced between 250 and 300 mm apart. The *Hedera* were a 50/50 mix of *H. helix* 'Glacier' (Johnsons of Whixley, Yorkshire, UK) and *H. helix* (propagated in house), planted in December 2011. Additionally, at the end of April 2014, two months before the start of experiment 1, the *Hedera* plants around eight 'buildings' were pruned to approximately 200 mm thickness at the sides and for four of the *Hedera*-covered buildings, the top was pruned in line with the upper concrete slab (forming the roof of the model 'buildings') and for the other four the *Hedera* was pruned to half-way up the building.

During spring 2015 (experiment 2), *Hedera* coverage was not as dense as during summer 2014 due to damage sustained when buildings were mortared in January 2015. Following building mortaring, the plants were replanted in April 2015 and pinned where necessary. The number of plants replanted to maintain robust coverage was on average one extra *Pileostegia viburnoides*, six to seven *Parthenocissus tricuspidata,* and two *H. helix* per appropriate cuboid. Additional three-year-old *Parthenocissus tricuspidata* 'Veitchii' plants were sourced from New Leaf Plants Ltd, Evesham, UK.

For the ivy management experiments (3i and 4), juvenile (vegetative phase) *H. hibernica* (supplied by Fibrex Nurseries Ltd, Pebworth, UK), were purchased as six- to nine-month-old plants, separated into single stems and potted into 275 mL containers, then placed in a ventilated glasshouse (see section 2.2) and regularly watered for eight weeks prior to the start of the experiments.

For the laboratory-based cuttings experiment (3i), two-year-old, vegetative phase *H. helix* (supplied by MacPennys Nurseries, Dorset, UK) was purchased and used as source material; juvenile cuttings of both *H. helix* and *H. hibernica* were excised 150 mm from the tip of the shoot. For the *in situ* field experiment (3ii), *H. helix* 'Glacier' was used, which had been planted in 2008.

2.3.1 Growing media

Whenever plants were transplanted into containers, they were re-potted in a peat-based medium (Vitax potting compost, Coalville, UK), with Osmocote® 9-12 month controlled release fertiliser used according to the manufacturer's instructions (The Scotts company, Maryville, US). Plants for use outdoors (experiments 1 and 2) were planted directly into the existing (freely draining loamy) soil, with added Osmocote® 9-12 months controlled release fertiliser applied as directed, to aid plant growth. The cuttings (experiment 3i) were grown in 15 mL test tubes filled with demineralised water with no additives.

2.4 Watering regimes

In field based experiments (1 and 2), to mimic potential domestic practice, the SMC was measured every two weeks, and plants watered if the SMC fell below < 0.15 m^3m^{-3}. In experiment 3i, plant cuttings were maintained in demineralised water, which was topped up twice weekly. Regulated deficit irrigation was applied in experiment 4, where SMC was maintained at > 0.25 m^3m^{-3} (to produce a 'well-watered' treatment) or < 0.15 m^3m^{-3} (to produce a 'water-stressed' treatment).

2.5 Measured parameters; sensors and devices used

The parameters measured in all experiments are summarised in Table 2.1; variations in experimental methods, levels of replication, and modes of analysis are described in the experimental summary (section 2.10), or in appropriate chapters. Experiments 1 and 2 are presented in Chapter 3, while experiments 3 and 4 are presented in Chapters 5 and 6, respectively. Experiment 1 measured summertime temperature and RH, while experiment 2 focused on wintertime temperature and RH. In experiment 3 attachment force and aerial root parameters were measured and experiment 4 focused on shoot growth parameters and aerial root number.

Table 2.1 List of parameters/variables measured in each experiment

Parameter/variable measured	Exp. 1	Exp. 2	Exp. 3	Exp. 4
Substrate moisture content (SMC)	X			X
Leaf stomatal conductance to water vapour (g_s) and net carbon dioxide assimilation (A)	X			
Relative humidity (RH) and temperature	X	X		
Ambient temperature and RH	X	X		X
Leaf surface area/wall leaf area index/foliage depth	X		X	X
Leaf number			X	X
Mean stem diameter			X	
Stem length			X	X
Aerial root number			X	X
Fresh stem weight			X	
Dry biomass (stems, leaves, and aerial roots)			X	
Number of aerial root attachment sites and total attachment length			X	
Maximum vertical force required to detach the stem from the wall surface			X	

2.5.1 Substrate moisture content (SMC)

The volume of water per unit volume of substrate m^3m^{-3} (SMC) at 50 mm depth was measured in experiments 1 and 4 with an SM300 sensor attached to an HH2 Moisture Meter (Delta- T Devices Ltd, Cambridge, UK). In experiment 1, two measurements were made on the south side of each building (in the same location as temperature and RH measurements) then averaged for each treatment. Plants were watered if the SMC fell below 0.15 m^3m^{-3}. Measurements of SMC were made before those concerning leaf stomatal conductance of water vapour (g_s) and net carbon dioxide assimilation (A) and also occasionally during summer experiments in 2014/15. In experiment 4, two measurements were made per container, at least weekly. The SMC was not measured during winter periods of 2015 and 2016 (see experiment 2); they were mild damp winters and sufficient water for plant needs was assumed to be available.

2.5.2 Leaf stomatal conductance of water vapour (g_s) and net carbon dioxide assimilation (A)

The infra-red gas analyser (IRGA) utilised to measure leaf stomatal conductance and net carbon dioxide assimilation detect the concentration of gases in a sample chamber by analysing absorption of infrared wavelengths by a captured gas mixture and comparing with measurements within a reference chamber. Leaf stomatal conductance of water vapour (g_s) and net carbon dioxide assimilation (A) were measured using an LCi IRGA equipped with a broad leaf chamber (ADC Bioscientific, Hertfordshire, UK) and a light source. Initially light was supplied by a halogen bulb, (50 W, 12 V) and later a light emitting diode (LED) array (16 x 8 rows of LEDs), providing saturating light (> 1300 μmol m^{-2} s^{-1}) to stimulate maximum stomatal conductance and carbon dioxide assimilation in the leaf. The chamber was clipped over the leaf to be measured and the measurement recorded after two minutes.

In a pilot study, measurements g_s and A, were made on three plant species (*H. hibernica*, *Pileostegia viburnoides* and *Parthenocissus tricuspidata*) using an LC*i* portable IRGA. Five containerised plants of each species were tested (see section 2.3) and two young (current year's growth) and two old (the growth from the year before); fully expanded leaves were measured per plant, along with the SMC measured in two places in each container. The g_s and A were measured on well-watered plants (SMC > 0.25 m^3 m^{-3}) in ambient light levels. Measurements commenced on 22nd July 2013 and concluded on 23rd August 2013. The mean leaf stomatal conductance (± standard deviation) was 0.10 ± 0.03, 0.09 ± 0.03 and 0.03 ± 0.01 mol$m^{-2}s^{-1}$ for *H. hibernica*, *Pileostegia viburnoides* and *Parthenocissus tricuspidata* respectively. The mean net CO_2 assimilation (± standard deviation) was 6.9 ± 1.0, 7.5 ± 2.0, 2.8 ± 1.0 μmol$m^{-2}s^{-1}$ for *H. hibernica*, *Pileostegia viburnoides* and *Parthenocissus tricuspidata* respectively.

Additionally, the same parameters g_s and A, were measured *in situ* for three plant species (*H. helix, H. colchica* 'Dentata', and *Parthenocissus tricuspidata*) using specimens that were established for at least five years. On each plant five pairs of young, fully expanded, leaves (the current year's growth) and five pairs of old, fully expanded, leaves (growth from the year before) were measured, evenly spaced across the plant. The g_s and A were measured in ambient light levels on plants in water deficit (SMC < 0.15 m^3 m^{-3}) at the top 50 mm substrate; however, there was likely to be water available at greater depth. All measurements were made on 28th August 2013. Mean leaf stomatal conductance (± standard deviation) was 0.07 ± 0.03, 0.07 ± 0.01, and 0.06 ± 0.02 mol$m^{-2}s^{-1}$ for *H. helix, H. colchica* 'Dentata', and *Parthenocissus tricuspidata* respectively. Mean net CO_2 assimilation was 2.8 ± 0.6, 5.2 ± 0.0, 4.9 ± 2.6 $\mu molm^{-2}s^{-1}$ for *H. helix, H. colchica* 'Dentata', and *Parthenocissus tricuspidata* respectively.

The pilot study indicated that the *Hedera* spp. tested, *Parthenocissus tricuspidata*, and *Pileostegia viburnoides* all have low leaf stomatal conductance rates whether containerised or growing in the ground compared to tree and shrub species (0.05-1.25 $molm^{-2}s^{-1}$, Wullschleger et al. (1998)), and trees have low leaf stomatal conductance rates compared to other plant species (tree range 3.8-6.6 mms^{-1}, compared to cereals and crops 11-12 mms^{-1}, Schulze et al. (1994)).

In experiment 1 (on 17th July 2015), measurements of g_s and A were made on young, fully expanded leaves on all three species. Four leaves were measured on the south side of each model 'building' (three replicate model 'buildings' per species); these results are shown in Chapter 3.3.2.8, Table 9.

2.5.3 Measurement of relative humidity (RH) and temperature

In experiments 1 and 2, RH and temperature were measured 50 mm from the internal and external walls of the model 'buildings'. Readings were taken continuously every 10 seconds and averaged every 10 minutes, using RHT2nl probes (Delta-T Devices Ltd, Cambridge, UK) connected to a DL2e data logger (Delta-T Devices Ltd., Cambridge, UK). The RHT2nl probes were screened with radiation screens and positioned 200 mm above the ground (details of sensor positioning in relation to model 'buildings' are provided in section 2.8). The RH sensor was accurate to ± 2% and the temperature sensor was accurate to ± 0.1 ^{o}C.

Additional temperature measurements were made with screened thermistors (type Fenwal UUA32J2, in-house construction), placed 15 mm from the internal and external walls of the model 'buildings' at approximately 200 mm from the ground. These were connected to a DL2e data logger (experiments 1 and 2) and accurate to 0.2 ^{o}C.

In experiment 2, measurements of the oil temperature in the immersion heaters were made using a probe thermometer (TPI Digital Pocket Thermometer, Screwfix Direct Ltd, Somerset, UK), which was accurate to ± 1 ^{o}C.

Details of ambient temperature and RH measurement procedures are provided in section 2.2.

2.5.3.1 Sensors' calibration

Before the summer 2014 and 2015 experiments, all RHT2nl probes were calibrated for 12 hours, in a Weiss Gallenkamp controlled environment (CE) chamber (Weiss Gallenkamp, Leicestershire, UK).

The mean temperature and RH measured by the probes was compared to independent measurements of temperature and RH within the controlled environment chamber via the chamber's internal measurement system. Any individual probe that measured greater than 2% of the independently measured mean temperature/RH, was removed, replaced with a spare probe and re-tested. Before each experiment, the thermistors were additionally calibrated both at 0 ^{o}C in an ice bath and 70 ^{o}C in a water bath; thermistors measuring within 0.5 ^{o}C of those temperatures were kept. However, any deviating from that were replaced with a spare thermistor and re-tested.

2.5.4 Leaf surface area, wall leaf area index (WLAI), foliage depth, leaf number and aerial root number

Leaf surface area (without the petiole or stems, unless stated otherwise) was measured in experiment 1 using the WD3 WinDIAS leaf image analysis system and associated software WinDias 3.2 (Delta-T Devices Ltd, Cambridge, UK). Excised leaves were placed on a light box with a video camera overhead; once all leaves to be measured were visible in the frame a still image was 'captured'. Where leaves were thick or curled (for example, *Pileostegia viburnoides*), they were cut in half to ensure the full surface area was calculated. The instrument was calibrated daily before use.

The wall leaf area index (WLAI) was measured on 1st September 2015 after the summer experimental period (in experiment 1); a 150 x 150 mm square of foliage was excised from the west wall of each foliage-covered 'building', the surface area of the leaves within the square measured (as described above) and the WLAI (Cameron et al., 2014) calculated as per equation [2.1].

$$\frac{\boldsymbol{leaf\ surface\ area}}{\boldsymbol{wall\ surface\ area}} \qquad \textbf{[2.1]}$$

In July 2016, the mean depth of the foliage was measured with a ruler in three places on each wall around the model 'buildings'.

The number of fully unfurled leaves was recorded in experiment 3i, as were both aerial root primordia (raised 'nodules' in the stem before the aerial root is produced) and fully grown aerial roots. Aerial root primordia were included in the aerial root count as they indicated sites of future aerial root growth.

2.5.5 Stem diameter, total attachment length, aerial root and leaf weight

The stem diameter (in experiment 3i and ii) was quantified by taking two measurements, one from either end of the stem, using an unbranded electronic digital calliper (Maplin, Reading, UK), which were then averaged. The total attachment length of the aerial roots was also measured using the digital calliper. The fresh stem weight and the dry stem, aerial root, and leaf weights were measured with a CBK 32 bench checkweighing scale (Adam Equipment Ltd, Milton Keynes, UK).

2.5.6 Maximum vertical force to detach a stem from a surface

The maximum vertical force required to detach a cutting from a surface was measured in experiment 3i and ii, using an FH50 digital force gauge (Sauter GmbH, Balingen, Germany). In order to measure the maximum vertical detachment force, *Hedera*-covered panels were laid horizontally, the force gauge was then hooked (using a small piece of wire), under the ivy stem between two aerial root attachment points. The gauge was lifted vertically until the ivy shoot detached from the cork section, and the peak force of detachment was recorded (experiment 3).

2.6 Model 'building' construction and heating

The experimental set up was adapted from a previous PhD experiment (Taylor, 2012). The model 'buildings' (used in experiment 1, summer 2014) were built in the grounds of the glasshouse complex, at the University of Reading, UK (Figure 2.2). The 'buildings' were each made with 64 bricks (standard red clay brick (classified BSEN 771, Class B, 215 x 103 x 65 mm; thermal properties: k = 1.1 $Wm^{-1}K^{-1}$, Blockley's Brick Holdings plc., Telford, UK)), arranged in a stretcher bond (in which bricks are laid lengthways with no headers) to form walls half a brick thick, with grey concrete slabs forming the top and base. A 'damp course' layer (polypropylene tape 1.05 mm thick) was incorporated between the first and second layer of bricks. A layer of chicken wire was wrapped around each building to prevent the plants (particularly ivy) rooting into the cracks between the bricks. The external measurements of the 'model buildings' were 500 x 600 x 600 mm and the concrete slabs were 600 x 600 x 34 mm.

Figure 2.2 Aerial photograph of the model 'buildings' site in layout from Taylor (2012) experiments (from Google Maps)

2.6.1 Adapted building design (experiments winter 2015 onwards)

The model 'buildings' were re-constructed in January 2015 (between experiments 1 and 2) to more closely mimic a standard domestic/commercial building, using the following steps: the chicken wire was removed (as the plants were unlikely to root into a cement mortar), and the original concrete slabs and base layer of bricks were lifted and dried for two days at 70^{o}C, to reduce the moisture content. A layer of sand and cement mortar (ratio of 4 sand to 1 cement) was then applied to the weed resistant matting (MyPex®) to provide a level surface and a 1200 gauge (0.3 mm) damp proof membrane (DPM, Visqueen Building Products, Heanor, UK) laid upon the mortar. Finally, the model 'buildings' were reconstructed using the original bricks (including the dried base bricks and slabs) and mortar (see above), though top slabs were replaced with Metsä Wood oriented strand board (OSB, B & Q plc., Hampshire, UK; 600 x 600 x 11 mm) with 1.3 mm B & Q value bitumen shed felt (B & Q plc., Hampshire, UK) secured with clout roofing nails (B & Q plc., Hampshire, UK), providing a 50 mm overhang on the north and south sides and a 100 mm overhang on the east and west sides (Figure 2.3 and 2.4). To prevent the formation of air gaps, the DPM was secured to the dried base brick layer with double sided waterproof membrane joining tape (Visqueen Building Products, Heanor, UK), wrapped around said layer, then sealed with Sika® Multipurpose-BT (Butyl sealing tape) weatherproof single-sided flashing tape (Sika, Baar, Switzerland). The DPM was held in place by the next brick layer before being mortared in place to prevent any water incursion. There was no overlap of any DPM material into the inside of the structure, so trapped water could not enter model buildings along the DPM. While it is not a standard construction method to use two DPMs, this was done in this case to reduce moisture infiltration from the soil via the concrete slabs which formed the base of each building. A suspended timber floor was constructed inside each building, above the DPM. This floor was constructed using a 401 x 311 x 18 mm section of marine ply as a base. An equivalent sized piece of multi-layer air bubble film insulation with aluminium bonded to both faces (Diall Aluminium Radiator Reflector Roll ‘silvered insulation’; B & Q plc., Hampshire, UK), was sandwiched between six batons (20 x 311 x 18 mm), three per layer, which were then nailed to the ‘floor’. This created two 18 mm air gaps, one above and one below the ‘silvered insulation’. The ‘floor’ was secured in place with Diall weatherproof external silicone (B & Q plc., Hampshire, UK). The suspended timber floors were intended to prevent condensation gathering on the base of the building. Similar batons were also fixed to the OSB which formed the roof on the model building, further ‘silvered insulation’ was then secured over the batons, with a 20 mm overlap onto the brick and an 18 mm air gap between the OSB and the ‘silvered insulation’ (Figure 2.3 and 2.4).

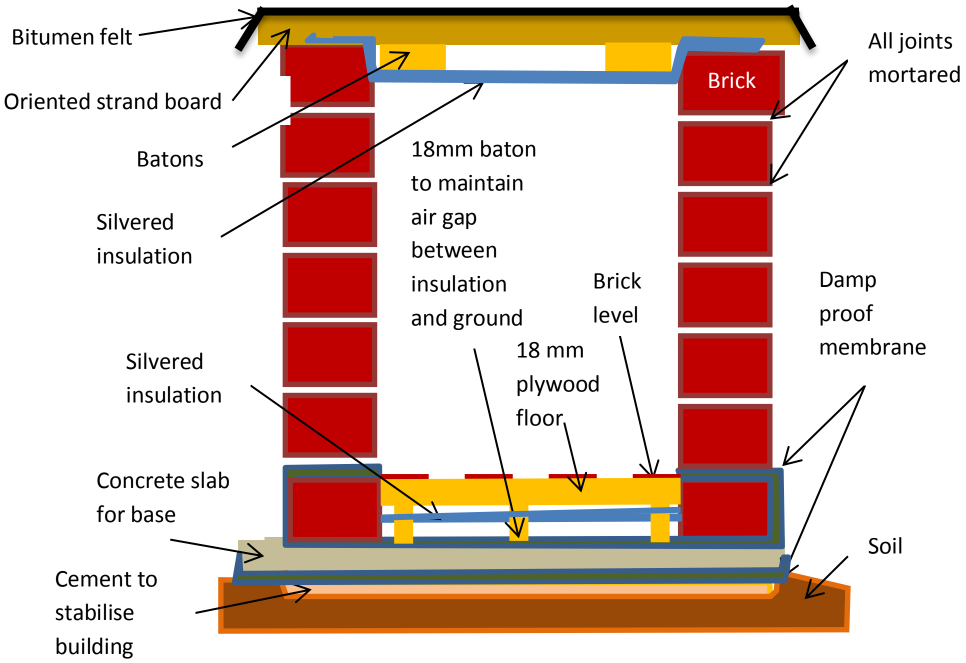

Figure 2.3 Diagram of model ‘building’ construction, January 2015 onwards (not to scale)

Figure 2.4 L-R: Bare model ‘building’ without roof (left) and with roof and RHT2nl sensors *in situ* (right) (Photographs by Faye Thomsit-Ireland)

During the spring 2015 and winter 2016 experiments the model 'buildings' were minimally heated. As measurements of RH were made during experiments 1 and 2, any heating device installed within the model 'buildings' had to be chosen so that it would not generate moisture. While commercial oil-filled radiators are sealed units and therefore do not produce water vapour, no currently available example offered the required combination of small size, multiple settings and relatively low power. The lowest power available (400W) lacked flexibility, in terms of temperature settings, and was likely to overheat the 0.12 m^3 space available within the model 'buildings'. Preliminary tests indicated that a 75 W aquarium heater (Protx 1020, 75 W thermostatic heater, AquaCare Inc., Illinois, US and HT-810, Hidom, China) submerged as an immersion heater in 5 L of vegetable oil (KTC (Edibles) Ltd., Wednesbury, UK), would provide a suitable substitute (Figure 2.5). The glass surrounding the aquarium heater did not become hot and the heating element was screened, thus reducing the chance of radiative interference with the temperature loggers. The thermostatic control on the aquarium heaters was set to 30 ^oC.


Figure 2.5 L-R: Oil bottle immersion heater (left) and immersion heater in the building (right), during the experiments the heaters were in the centre of the building (Photographs by Faye Thomsit-Ireland)

2.7 Model 'building' layout

The layout of experiments 1 and 2 is shown in Figure 2.6. The treatment for each building was chosen using a partially randomised design, where the established *Hedera* plants were left in place and every treatment had at least one 'building' on the inside of the group of 'buildings' and between two and three on the outside of the group, to represent being sheltered or exposed (however, aspect was not considered). For the summer 2014 experiment, four model buildings per treatment were prepared. Due to changes in sensor positioning, however, from the spring 2015 experiment three model 'buildings' per test species were used (Table 2.2). Wall-to-wall distances between the buildings were 1.5 m on the N-S axis, and 1.75 m on the E-W axis.

Figure 2.6 Model 'building' layout schematic and the plant cover around them (not to scale)

The model 'buildings' used in experiments 1 and 2 are shown in Table 2.2 and Figure 2.7. Buildings 2, 7, 12 and 13, were covered in *Hedera* cut to halfway up the building; however, they were not used when analysing the experiments.

Table 2.2 Model 'buildings' used in experiments

Experiment	Season and year	Buildings used	Building state
1	Summer (July and August 2014)	1, 3, 4-6, 8-11, 14-20	Unmortared
1	Summer (June and July 2015)	1, 3, 6-8, 11, 14-16, 18-20	Mortared
2	Spring (March 2015)	3, 4, 10, 15, 18, 20	Mortared
2	Winter (January to February 2016)	1, 3, 6-8, 11, 14-16, 18-20	Mortared

Figure 2.7 Model 'buildings' measured in experiments 1 and 2 and modelled in Chapter 4, not all buildings represented were used (Photograph by Tijana Blanuša)

2.8 Sensor layout

The layout of the sensors varied between experiments. During summer 2014 (experiment 1), RH and temperature measurements were made continuously adjacent to the external south wall of each un-mortared model 'building', or behind the foliage in vegetated 'buildings'. An RHT2nl sensor was placed alongside a thermistor by the external wall (see section 2.5.3 for sensor distances from the wall). Temperature measurements were made continuously next to the internal south wall of each 'building', using a single thermistor per structure (Figure 2.8).

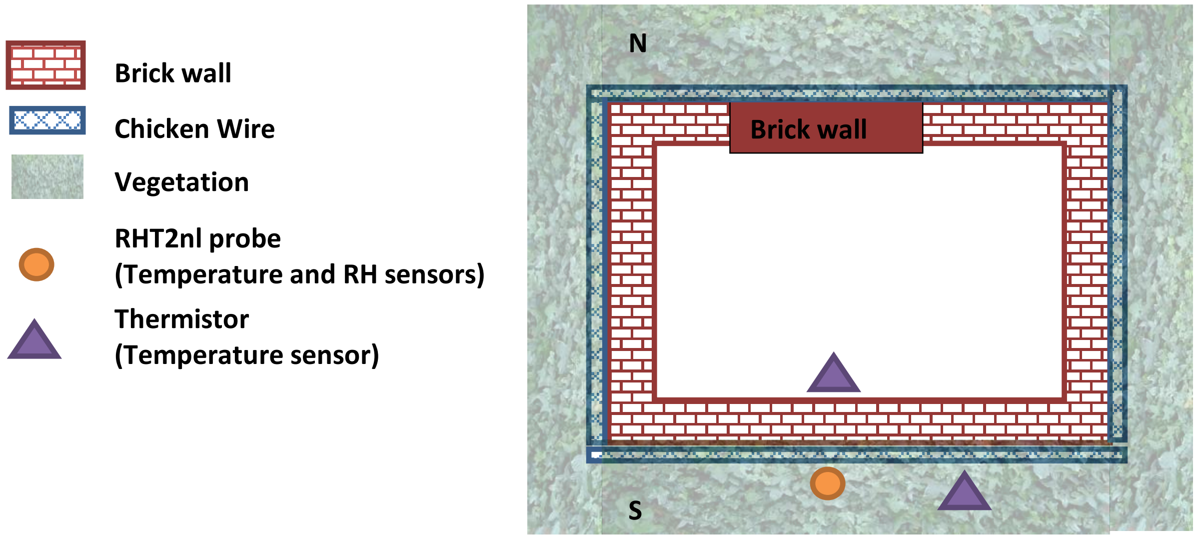

Figure 2.8 Sensor layout during summer 2014, not to scale (experiment 1)

The same scheme was repeated for the summer 2015 experiments, with the addition of a further thermistor at the external south wall of each building, complemented by an RHT2nl sensor placed at the internal side of the same wall (Figure 2.9). The plant cover and external building set up for the summer 2015 experiments is shown in Figure 2.10.

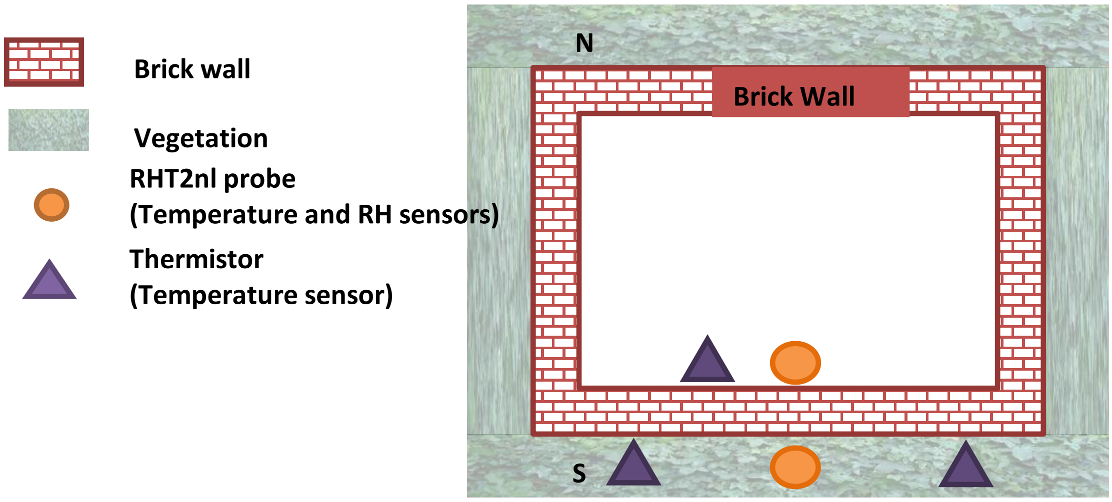

Figure 2.9 Sensor layout during summer 2015, not to scale (experiment 1)

Figure 2.10 Top left to bottom right: Bare model 'building' and 'buildings' covered with *Pileostegia viburnoides*, *Parthenocissus tricuspidata* and *H. helix*, with roof and sensors *in situ*: set up for summer 2015

During spring 2015 (experiment 2), RH and temperature measurements were made continuously by RHT2nl probes placed next to both sides of the north and south walls of the mortared model buildings, complemented by paired thermistors at the internal walls only (Figure 2.11). Once the results were analysed, however, temperature and RH readings made at the north wall were not significantly different from those made at the south wall, so these data were excluded from analysis to maintain comparable datasets between the years and seasons. The temperature data recorded at the three south positions (SE, S and SW) were averaged for use in Chapter 3.

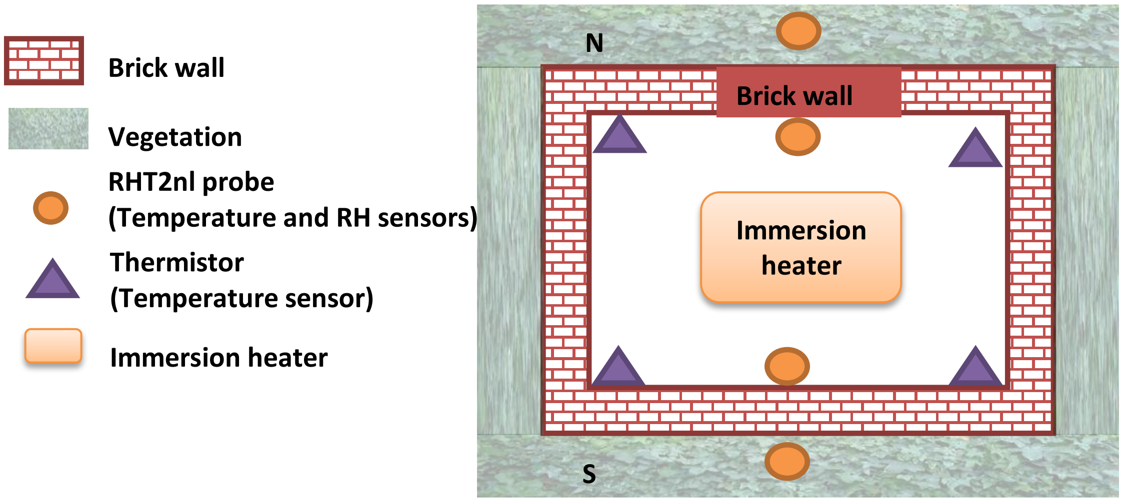

Figure 2.11 Sensor layout during spring 2015, not to scale (experiment 2)

During winter 2016 (experiment 2), the RH and temperature measurements were made continuously next to the external south walls of the mortared model 'buildings'; using an RHT2nl probe. The temperature and RH were also measured continuously next to the internal south wall with another such probe. Due to the thermistors' logger malfunctioning, only RHT2nl probes were utilised during winter 2016 (Figure 2.12).

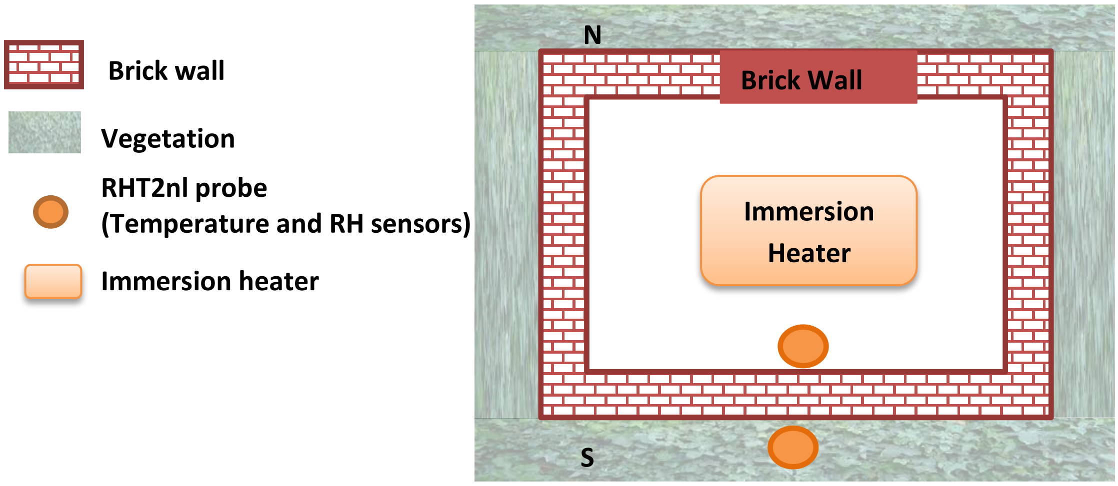

Figure 2.12 Sensor layout during winter 2016, not to scale (experiment 2)

2.9 Statistical analysis

Throughout this thesis means are calculated and are presented with the standard deviation (SD) of the appropriate data set. The standard deviation was omitted where values were the difference of means.

An analysis of variance (ANOVA) was conducted using GenStat (16th Edition, Lawes Agricultural Trust, Rothamsted Experimental Station, UK). Variances were checked for homogeneity and values were presented as means with the least significant differences (LSD; where the ANOVA was significant). Where a logarithmic transformation improved the normality of the residuals (after visual assessment), this was used to discover whether parameters were significant; all values in the thesis results chapters are, however, presented in an untransformed state for ease of interpretation.

Where other specific statistical tests were used within an experiment (for example, experiment 3), they are explained in the methods section of that chapter.

2.10 Summary of individual experiments

Experiment 1: The influence of vegetation on temperature and RH in and around unmortared model 'buildings' (summer 2014) and mortared model 'buildings' (summer 2015)

In summer 2014, four unmortared 'buildings' (with chicken wire wrapped round them to prevent the plants rooting into the cracks between the bricks) were prepared per treatment with five treatments (20 'buildings' in total, see section 2.6 for construction details). The treatments were bare (control), *H. helix* established since 2011 pruned to either the 'roof-line' or to half-way up the building, *Parthenocissus tricuspidata* and *Pileostegia viburnoides* (see section 2.7 for 'building' layout). In April 2014, the *Parthenocissus tricuspidata* and *Pileostegia viburnoides* were planted and the *Hedera* was pruned, (see section 2.3 for details of plant provenance, pruning, and age). There were eight plants used for each 'building' (two on each side of the 'building'). The summer 2014 experiment was conducted between 16th July and 29th August 2014.

Before the summer 2015 experiment, the buildings were mortared (in January 2015) as detailed in section 2.6.1 and the chicken wire was removed. In April 2015, additional plants were established where coverage was patchy or plants had died during the mortaring process. On average, one additional *Pileostegia*, six additional *Parthenocissus*, and two additional *Hedera* were planted per 'building' as appropriate for the treatment. The summer 2015 experiment was conducted between 24th June and 20th July 2015.

Experimental setup summary:

Summer 2014: five treatments (bare 'buildings', or covered with *Hedera* (pruned to half-way up the 'building' or to the roofline), *Parthenocissus* or *Pileostegia*), four replicates (unmortared model 'buildings') per treatment.

However, in the preliminary statistical analysis, there were no significant differences between the *Hedera*-covered 'buildings' with half or full coverage therefore the *Hedera*-covered 'buildings' with half coverage were excluded from the results presented in Chapter 3.

Summer 2015: four treatments (bare 'buildings', or covered with *Hedera* (pruned to roofline), *Parthenocissus* or *Pileostegia*), three replicates (mortared model 'buildings') per treatment.

Measurements made:

Both summer 2014 and 2015: air temperature and RH in front of the south wall (behind foliage where appropriate), air temperature by the south wall inside the 'building' (see section 2.5.3, Figure 2.8 and 2.9) local ambient weather conditions (monitored by High Wycombe MO and UoR MO).

Additional measurements made in summer 2015: RH by the south wall inside the 'building' (see section 2.5.3, Figure 2.9), SMC (see section 2.5.1), LAI (see section 2.5.4), g_s, A (see section 2.5.2).

Experiment 2: Temperature and RH in and around mortared model 'buildings' as influenced by evergreen plants during spring 2015 and winter 2016

The spring 2015 experiment considered mortared *Hedera*-covered 'buildings' and bare 'buildings' (Table 2.2, experiment 2), which were heated using immersion heaters (construction and heater details see section 2.6.1). These were planted as described in the summer 2014 experiment (see section 2.10 experiment 1). Temperature and RH at the north side of each model building were measured during spring 2015 experiment (Figure 2.11); however, as there were no significant differences between temperatures and RHs measured on the buildings' north and south sides, the north side data was excluded from the analysis in Chapter 3. The spring 2015 experiment was conducted between 6th and 27th March 2015.

In winter 2016 the *Parthenocissus*- and *Pileostegia*-covered 'buildings' were measured in addition to bare 'buildings' and *Hedera*-covered 'buildings' (Table 2.2, experiment 2). As there were no significant differences between data acquired from the *Parthenocissus*- and *Pileostegia*-covered 'buildings' and that from the bare 'buildings', these were excluded from the analysis in Chapter 3. This was not unexpected for either treatment as *Parthenocissus* is deciduous and *Pileostegia* had produced intermediate results during summer. The winter 2016 experiment was conducted between 14th January and 4th February 2016. From the 18th January 2016 heaters (as described in section 2.6.1) were installed inside the 'buildings'.

Experimental set up summary:

Spring 2015: two treatments (*Hedera* and bare 'buildings'), three replicates (mortared model 'buildings')

Winter 2016: four treatments (*Hedera*, *Parthenocissus, Pileostegia* and bare 'buildings'), three replicates (mortared model 'buildings')

Measurements made:

During both spring 2015 and winter 2016: air temperature and RH by the external south wall (behind foliage where appropriate) air temperature and RH by the internal south wall (see section 2.5.3, Figure 2.11 and 2.12), local ambient weather conditions (monitored by UoR MO).

Additional measurements made during spring 2015: air temperature and by the external north wall (behind foliage where appropriate), air temperature and RH by the internal north wall (see section 2.5.3, Figure 2.11).

Experiment 3: Manipulation of a building surface to reduce *Hedera* aerial root attachment:

i) Screening of cuttings in a laboratory setting: Sixty shoot tips of juvenile *H. helix* and *H. hibernica*, each 150 mm long, were excised and maintained in 15 mL vials containing demineralized water (see section 2.3). This experiment was conducted between 1st May and 10th July 2014.

Excised shoots were grown in close proximity to 100 x 100 mm cork panels (Boulder Developments Ltd, Norwell, UK). Cork was used as it lacks a grain, therefore can be used in any orientation. In a study by Melzer et al. (2012) a cork substrate was resistant to failure during *Hedera* detachment, and is therefore likely to provide information about the maximum attachment strength of *Hedera* aerial roots. Additionally, cork can be easily applied to a variety of surfaces without any skilled labour (as would have been required to create cement render or mortared brick facings) and, furthermore, could be used immediately without weathering. While there has been no work on interactions between *Hedera* aerial roots and anti-graffiti paints the rationale behind the choice of paints for this experiment is described in Chapter 5 section 5.1. Cork panels were treated with the following to produce a total of five treatments:

a. Two coats of an anti-graffiti paint 'Easy-On': a silane-based, nanoparticle paint (Urban Hygiene Ltd, South Yorkshire, UK);

b. Two coats of an anti-graffiti paint 'Pegagraff® hydro': an organic, petrochemical-based paint (Mathys Corporate, supplied by Graffiti Magic, Kent, UK);

c. Copper sheet, thickness 0.7 mm (Cooksongold, Birmingham, UK) attached to cork with adhesive (UHU All-purpose adhesive, UHU GmbH & Co. KG, Bühl, Germany);

d. Zinc sheet, thickness 0.4 mm (Fab Flash Self-Adhesive Soft Zinc Alloy Flashing, Roofing Superstore, Devon, UK) attached to cork as above;

e. Control (bare, untreated cork).

One week before the start of the experiment to allow solvents to evaporate from the paints and adhesives, treatments were applied and sections were then mounted onto 300 x 300 mm plywood panels (Figure 2.13).

Figure 2.13 Laboratory set up to show construction of the panels, this shows one panel (block) and only three of the five treatments are presented here due to the balanced incomplete block design (Johnstone, 2013; photograph by Faye Thomsit-Ireland)

Vials and treatments were set-up in a balanced incomplete block design (Johnstone, 2013) within the laboratory environment. Figure 2.14 shows the experimental arrangement of shoots and treatments on one panel (block); per treatment replicate there were two *H. helix* shoots and two *H. hibernica* shoots (shoots of the same species were placed next to each other, in separate vials). The species order i.e. whether *H. helix* or *H. hibernica* shoots were first on the treatment replicate was randomised. There were 10 blocks (the 10 model panels), and six replicates (averaged from 12 pseudo-replicates, two shoots per treatment replicate) per species for each of the five treatments. A thigmotrophic response (to produce aerial roots) was encouraged in the cuttings by supporting them with drawing pins and insulating tape as appropriate (Figure 2.14).

Figure 2.14 L-R: *Hedera* cuttings in a laboratory set up growing over zinc sheet, cork control, and copper sheet (Photograph by Faye Thomsit-Ireland)

ii) Outdoor field trials

Two walls on a brick building at the UoR Whiteknights campus were used for this experiment (Figure 2.15), with *H. helix* 'Glacier' (see section 2.3), grown next to the building wall. These *Hedera* plants were pruned yearly in September. At the start of the experiment, three panels were constructed from 1400 x 350 mm plywood with six 240 x 300 mm treated cork sections mounted on each panel according to a complete block design (Figure 2.16; Johnstone (2013)). The panels were attached to the building walls at the yearly pruning height. The experiment was conducted between 26th May and 15th September 2014.

Figure 2.15 Outdoor experiment with three treatments, anti-graffiti paint 'Easy on', copper mesh and control (untreated) cork. There are two panels shown, one on each building wall, on each panel there are two replicates of each treatment, L-R: anti-graffiti paint 'Easy on', control, copper mesh, anti-graffiti paint, control, copper mesh, while this may appear non-random, the pattern occurred due to the small number of treatments (Photograph by Faye Thomsit-Ireland)

Figure 2.16 A panel at the start of the outdoor experiment; showing two replicates of each treatment L-R: control, copper mesh, anti-graffiti paint 'Easy on', control, anti-graffiti paint and copper mesh (Photograph by F. Thomsit-Ireland)

There were three treatments (Figure 2.16):

a. Two coats of anti-graffiti paint 'Easy-On' (Urban Hygiene Ltd, Doncaster, UK) on a cork base;

b. Copper mesh #60, 0.263 mm Aperture - 0.16 mm Wire Diameter (The Mesh Company Ltd, Warrington, UK) attached to cork with drawing pins;

c. Control (bare, untreated cork, Boulder Developments Ltd, Norwell, UK).

Treated cork sections were prepared as per the experiment 3i. Two treatment replicates were applied per panel in a complete block design (Figure 2.15 and 2.16). The ivy was then allowed to climb the panels naturally, resulting in between nine and twenty shoots attached to each treatment replicate (Figure 2.17). Measurements made on each shoot from a treatment replicate were averaged to give a mean measurement per treatment replicate, which was then subjected to statistical analysis. There were, therefore, three treatments, with six replicates per treatment and three blocks (for the three panels).

Figure 2.17 One of the panels after 14 weeks of growth, with two replicates of each treatment, L-R: anti-graffiti paint 'Easy on', control, copper mesh, anti-graffiti paint, control, copper mesh (Photograph by Faye Thomsit-Ireland)

Experimental setup summary:

i) Shoot tip cuttings (150 mm), two species (*H. helix* and *H. hibernica*), five surface treatments (two anti-graffiti paints ‘Easy-On’ and ‘Pegagraff’, copper sheet, zinc sheet, and bare cork (control)), and six replicates of each treatment for each *Hedera* species.

ii) Mature plants *H. helix* ‘Glacier’ *in situ*, three surface treatments (anti-graffiti paint ‘Easy-On’, copper mesh, bare cork), and six replicates of each treatment.

Measurements made:

i) Initial measurements made (on 1st May 2014) were mean stem diameter, fresh stem weight, leaf number, and aerial root number (see sections 2.5.4 and 2.5.5). Subsequently, leaf number and the number of aerial root attachment sites were counted every two weeks. It was important not to disturb the cuttings as they were attaching, as bonds made with unfavorable surfaces could be very weak. Final measurements including stem length, total attachment length (section 2.5.5), leaf surface area (see section 2.5.4), aerial root weight and maximum vertical force required to detach cutting were made on 10th July 2014 (see section 2.5.6).

ii) To detach the panels from the walls for analysis *Hedera* shoots were trimmed at the yearly pruning line below the panels using a scalpel, then each panel was wrapped in clingfilm to ensure that the shoots remained in place. Where shoots had moved between treatments, they were divided with a scalpel along the gaps in between the cork sections (treatment replicates), and trimmed at the base of the treatment. There were between nine and twenty shoots covering each treatment replicate, therefore shoot measurements (listed below) were averaged to provide a mean measurement for each treatment replicate. Measurements were made at the end of the experiment (15th September 2014), once all panels had been detached from the wall. These measurements included the maximum vertical detachment force for each shoot (see section 2.5.6), stem breakage, shoot length from the bottom of the cork section (treatment replicate), stem diameter (two measurements made in the centre of the stem see section 2.5.5), total attachment length (see section 2.5.5), leaf surface area (see section 2.5.4), and dry biomass (total biomass (stem, leaves and aerial roots); aerial roots; and leaves see section 2.5.5).

Experiment 4: The effect of water deficiency and container size on plant growth and aerial root production in *Hedera* plants

A factorial experiment with five replicates per treatment, arranged in a randomised design, was set up in the UoR glasshouses (see section 2.2). Twenty *Hedera hibernica* plants (see section 2.3) were transplanted into 2 L containers (10 plants) and 275 mL containers (10 plants), watered to capacity and pruned to the fourth node from the initial propagation cut. These plants then established over the next 14 weeks while the watering regime was established and, in the case of the small containers, become pot-bound. The 2 L ('large') and 275 mL ('small') containers were hand watered to substrate moisture content (SMC) of either > 0.25 m^3m^3 ('well-watered') or < 0.15 m^3m^3 ('stressed'). Therefore, treatments were 'container size' and 'watering regime'. Measurements commenced on 4th November 2013 and concluded on 4th March 2014.

Experimental setup summary:

Four treatments: 'large well-watered' (2 L container and SMC > 0.25 m^3m^{-3}), 'small well-watered' (275 mL container and SMC > 0.25 m^3m^{-3}), 'large stressed' (2 L container and SMC < 0.15 m^3m^{-3}), and 'small stressed' (275 mL container and SMC < 0.15 m^3m^{-3}). Each treatment was replicated five times.

Measurements made:

The SMC was initially measured twice weekly, then weekly once the watering regime became established (see section 2.4). Stem length, number of leaves, and number of aerial roots were all measured every two weeks for the duration of the experiment.

Chapter Three

Understanding the impact of vegetation on temperature and relative humidity (RH) around and within model 'buildings'

3.1 Introduction

It has been established that anthropogenically induced global warming is occurring and causing widespread environmental disruption (Bernstein et al., 2007). Approximately 25% of global GHG emissions relate to heat and electricity production, therefore reducing the need to heat and cool buildings will reduce GHG emissions (EPA, 2017). Within Britain, approximately 85% of housing stock is constructed with materials that have twice the thermal conductivity of current standards, materials that are less insulating (Hamilton et al., 2013), which leads to increased energy use to maintain thermal comfort. Green walls may form part of an integrated solution to these problems.

There are three ways that green walls may reduce thermal fluctuations around buildings: cooling (via evapotranspiration and shading) and insulation. Cooling from evapotranspiration and shading, however, are typically considered together as they cannot easily be separated. Studies have shown that on hot days, structures behind foliage were significantly cooler, both within and without, than those left bare (Di and Wang, 1999, Ip et al., 2004, Miller et al., 2007, Ip et al., 2010, Pérez et al., 2011a, b, Cameron et al., 2014). Plant species such as *Fuchsia* and *Hedera* had different cooling potentials, caused by a combination of shading and evapotranspiration differences between species (Cameron et al., 2014). Additionally, the dominant cooling effect is dependent on the plant variety used in the greening scheme. *Parthenocissus* grown across windows to provide shade also increased the humidity inside the building by between 5% and 14% between July and October (indicating evapotranspiration processes) compared to bare buildings (Miller et al., 2007). The thermal effects detected are, however, affected by aspect; shading effects are typically more pronounced on the south wall in the northern hemisphere, as there are more solar gains (Cameron et al., 2014). Furthermore, these effects have only occasionally been studied at night or during spring/autumn where the effects will be more marginal (Di and Wang, 1999, Cameron et al., 2014).

Insulation effects may become more prominent, however, during cooler periods where cooling via evapotranspiration and shading is reduced. During full days in winter, dense *Hedera* grown round model 'buildings' increased external wall temperatures by between 1.6 and 3 ^{o}C depending on the weather conditions, compared to bare bricks (Cameron et al., 2015). The *Hedera*-covered model 'buildings' also used less energy for heating and emitted less thermal energy than bare model 'buildings' (Cameron et al., 2015). This is in agreement with another study showing the thermal resistance of *Hedera* foliage and the insulating effects of the *Hedera* foliage (Ottelé and Perini, 2017). Furthermore, the daily temperature variation of a wall surface behind *Hedera* foliage has also been found to be reduced compared to a bare wall surface (Sternberg et al., 2011b). Therefore *Hedera* may be capable of acting as a multipurpose solution to issues of thermal comfort.

Historically there has been an on-going debate concerning the extent to which *Hedera*-cladding causes damp problems by preventing evaporation from the wall (Taddyforde et al., 1877, Muckley, 1886), which continues to this day (BRE et al., 1996, Douglas & Noy, 2011, Sternberg et al., 2010b, Ottelé, 2011). According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers ASHRAE Standard 62-2001 (ASHRAE, 2001), the internal atmosphere should be maintained at 30 to 60% RH for ideal air quality and comfort. If the RH rises above 60% for 24 hours or more, mould and dust mite growth may increase, which can have a detrimental effect on human health (ASHRAE, 2001). Additionally if walls become damp, the thermal conductivity of the walls increases, thus increasing heat losses (Kumaraperumal, 2009). This problem may be reduced by using taxa such as *Hedera,* along with *Parthenocissus* and *Pileostegia* which display relatively low rates of evapotranspiration (preliminary studies, Chapter 2, section 2.5.2).

Relative humidity is a function of absolute humidity (the moisture content of the air) and temperature; as the temperature increases the RH decreases (Green and Perry, 2007). Therefore in situations where the greatest temperature disparity would occur between greened and bare walls the highest RH differences would also occur. As the British maritime climate has frequent periods of low temperatures, there may be grounds for concern over the use of *Hedera* in this country, in terms of its possible impact of increasing RH in and around buildings.

The primary natural source of moisture for any building envelope (not due to leaky guttering or a burst pipe) is driving rain (D'Ayala and Aktas, 2016). The building aspect primarily impacted by wind driven rain depends on the location and prevailing winds, therefore varies from city to city (Karagiozis et al., 2003). Building material is also a factor: sandstone is more vulnerable to damp incursion than bricks. The absorption coefficient of the material can provide an indication of the vulnerability of the material to moisture incursion (Kumaraperumal, 2009) therefore should be taken into account before any structural greening is considered.

Furthermore, Rath et al. (1989) found no difference in the moisture content of exterior plaster and brickwork between *Hedera* and *Parthenocissus* greened walls versus those left bare. This implies that any increase in RH will be offset by the lack of rain reaching the building, therefore buildings that are not damp before greening, should be fine thereafter however; this required further testing. Additionally when walls were covered with *Hedera*, there was evidence that the temperature and humidity stabilisation provided by the *Hedera*-covering would reduce the risk of frost and salt deterioration (including historic buildings and limestone buildings; (Sternberg et al., 2011b)).

As a result of client concerns, landscape designers and architects tend to avoid the use of vegetation around buildings (R. Griffin and C. Trickey, personal comment). It is therefore necessary to determine whether *Hedera* and other species used in direct greening can cause damage to buildings through increased RH and under which circumstances.

Experiments 1 and 2 (see Chapter 2, section 2.10 for summaries) are presented in this chapter, and investigate the effects of three plant species (*Hedera*, *Parthenocissus* and *Pileostegia*) on the daily external and internal temperatures and RH of a model 'building'. The times chosen for analysis were based on the maximum and minimum ambient temperatures, as determined by the UoR meteorological observatory (MO), during the period of the most stable ('flattest') parts of the diurnal temperature variation. In summer the coldest part of the day typically occurred between 03:00 and 05:00 British summer time (BST), while in the winter/early spring the coldest time occurred between 05:00 and 07:00 Greenwich mean time (GMT). However, the warmest part of the day typically occurred between 14:00 and 17:00 during both summer and winter/early spring.

The hypotheses were:

1. The presence of foliage will cool the building envelope during the day compared to the bare (unvegetated) buildings.

It was hypothesised that when temperatures are at their highest (summer afternoons between 14:00 and 17:00 BST), the impact of foliage will be most noticeable as the cooling effects of evapotranspiration and shading (the latter reduces solar gain) will be greatest.

2. Internal and external wall temperatures will be less variable for vegetated 'buildings' than the internal and external temperatures of bare 'buildings' during both summer and winter.

It was hypothesised that the internal and external temperatures of vegetated 'buildings', especially during summer, are likely to be more stable than the internal and external temperatures of bare 'buildings', as vegetated 'buildings' will be buffered (to an extent) against changes in the ambient temperature.

3. Daytime RH in summer will be higher behind foliage than in front of bare 'buildings'.

It was hypothesised that, when compared with the RH of bare buildings, the greatest increase in RH will occur during the hottest part of the day (14:00-17:00). Additionally while the vegetation will not increase the RH at night, it may trap water vapour emitted during the day.

4. The presence of foliage will provide some insulation effects which will primarily be apparent at night and during winter.

It was hypothesised that during the night (both in summer and winter) foliage cover will insulate the brickwork, preventing excessive cooling. The bare 'buildings' would, therefore, be coldest at this time (03:00-05:00 BST summer and 05:00-07:00 GMT winter/early spring); hence temperatures would be comparatively greater behind the vegetation. Foliage density may contribute to the effect; therefore temperatures will be highest behind the *Hedera* foliage followed by *Pileostegia* and then *Parthenocissus*.

3.2 Methodology

Details of the experimental set-up and measurement periods are provided in Chapter 2, sections 2.5 to 2.8 and 2.10; this chapter refers to experiments 1 and 2. The design of the 'buildings' used in each experiment is outlined in Chapter 2, section 2.7, Table 2.2. Information on sensors used and their set up within the experiments is provided in Chapter 2, sections 2.5 and 2.8. Ambient temperatures were recorded at the University of Reading (UoR) meteorological observatory (MO), except during summer 2014 when an error within the UoR MO meant data from the nearest other station (High Wycombe) was used instead (see Chapter 2, section 2.2).

Maximum temperature differences between bare and vegetated walls were observed during the hottest part of the day (Di and Wang, 1999, Cameron et al., 2014). As long as plants remained well-watered, evapotranspiration will occur at its highest rate during the hottest part of the day (Atwell et al., 1999), and therefore the greatest differences in evapotranspiration between species (and thus RH) will likely occur during this time.

This experiment also assessed the impact of vegetation on the temperature and relative humidity of the model 'buildings' during times representing the extremes of ambient temperatures measured during the experimental period. The coldest ambient temperatures were assessed during the morning periods in spring and winter, and the warmest ambient temperatures were assessed during the afternoon periods in summer. These data were then analysed for 'mornings' (05:00-07:00 GMT in winter/early spring and 03:00-05:00 BST in summer) and 'afternoons' (14:00-17:00 in all analysed seasons) to correlate with the coldest and warmest parts of the day, as assessed from the ambient weather data (section 3.1).

Data was extracted from the data loggers, and then arranged into a format suitable for statistical analysis and graph generation. This was performed in a programme written in C++ by James Thomsit, according to the specifications required for this project.

It should be noted that the model 'buildings' are experimental models, not constructed as domestic or commercial buildings would be (see Chapter 2, section 2.7 for details), hence the values for RH and temperature gained here will only be indicative of trends that may be found in 'typical' constructions. The information gained from experiments 1 and 2 could, however, still be used to guide legislation or building recommendations in the future.

3.2.1 Summer 2014

Dates with weather conditions representing 'warm' and 'cold' summer days were selected as the seven warmest and four coolest from the monitored days. In summer 2014, 17th to 19th, 23rd to 26th July were selected as 'warm' days (where the mean ambient temperature between 14:00 and 17:00 BST at the High Wycombe MO was > 23.5 ^{o}C); the 'cold' days selected were, 19th to 21st, 23rd August 2014 (where the mean ambient temperature between 14:00 and 17:00 at the High Wycombe MO was < 14 ^{o}C). Unmortared 'buildings' 1, 3, 4-6, 8-11, 14-20 were used for measurements and analyses (see Chapter 2, section 2.7; for sensor layout please see Figure 2.8 and section 2.8). Once days were selected according to the criteria above, both mornings and afternoons, from 03:00-05:00 BST and 14:00-17:00 BST respectively, were analysed.

3.2.2 Summer 2015

In summer 2015, the six warmest and five coolest days were analysed. The 29th, 30th June, and 1st, 3rd, 4th, 16th July were selected as 'warm' days (where the mean ambient temperature between 14:00 and 17:00 at the UoR MO was > 23 ^{o}C), and the 'cold' days selected were 28th June and 5th, 8th, 12th, 13th July 2015 (where the mean ambient temperature between 14:00 and 17:00 at the UoR MO was < 19 ^{o}C). Mortared 'buildings' 1, 3, 6- 8, 11, 14-16, 18-20 were used for measurements and analysis (see Chapter 2, section 2.7; for sensor layout see Figure 2.9 and section 2.8). Once days were selected according to the criteria above, both mornings and afternoons, from 03:00-05:00 BST and 14:00-17:00 BST respectively, were analysed. The WLAI (Wall Leaf Area Index) was measured on 1st September 2015 as described in Chapter 2, section 2.5.4.

3.2.3 Spring 2015

The five coolest and four warmest days were analysed in spring 2015. The 'cold' days were 9th, 11th, 18th, 24th, 25th March 2015, (where the mean ambient temperature from 05:00-07:00 GMT at the UoR MO was ≤ 3 °C), the 'warm' days were 7th, 8th, 12th, 13th March 2015 (where the mean ambient temperature from 05:00-07:00 GMT at the UoR MO was > 7 °C). Heated mortared 'buildings' 3, 4, 10, 15, 18, and 20 were used for measurements and analysis (see Chapter 2, section 2.7; for sensor layout see Figure 2.11, and section 2.8). Once days were selected according to the criteria above, both mornings and afternoons, from 05:00-07:00 GMT and 14:00-17:00 GMT respectively, were analysed.

3.2.4 Winter 2016

For winter 2016 the days analysed were:

'Cold' days without heaters installed inside the mortared 'buildings': 15th to 17th January 2016 (where the mean ambient temperature from 05:00-07:00 GMT at UoR MO was < 3 °C). These represented a baseline for comparison with later results.

'Cold' days with heaters installed inside the 'buildings': 19th to 21st, 28th January, and 3rd February 2016 (where the mean ambient temperature from 05:00-07:00 GMT at UoR MO was ≤ 3 °C).

'Warm' days with heaters installed inside the 'buildings': 24th, 25th, 29th January, and 1st February 2016 (where the mean ambient temperature from 05:00-07:00 GMT at UoR MO was > 9°C).

There were no days during the monitored period that correlated to the 'warm' day specifications when the heaters were not installed.

'Buildings' 1, 3, 6-8, 11, 14-16, 18-20, were used for measurements and analysis (see Chapter 2, section 2.7; for sensor layout see Figure 11 and section 2.8). Once days were selected for analysis according to the criteria above, both mornings and afternoons, from 05:00-07:00 GMT and 14:00-17:00 GMT respectively, were analysed.

3.2.5 Statistical analysis

The standard deviations were calculated using the full un-averaged data sets.

The data from each time period (for example, 14:00-17:00), and all the chosen days in the same scenario (for example, the 'cold' days during summer 2014), were averaged before running the ANOVA, which removed any temporal pseudo-replication.

3.3 Results

3.3.1 Depth of vegetation and percentage wall cover

During the experiment the depth of vegetation varied as plants became increasingly established (see Chapter 2, section 2.5.4 for details of measurements made). A visual estimation of wall coverage was made in July 2014, the percentage cover was estimated as 95 ± 10% for *Hedera*, 50 ± 8% for *Pileostegia* and 64 ± 17% for *Parthenocissus*. During the winter months of 2015 the *Hedera* plants were disturbed as the buildings were mortared which, during an additional visual estimation in March 2015, reduced the *Hedera* coverage to 40 ± 17%. In July 2015 a visual inspection estimated that the wall coverage was 89 ± 6% for *Hedera*, 99 ± 1% for *Parthenocissus*, and 84 ± 10% for *Pileostegia* (probably due to the nature of its crown development). In January 2016 the plants had similar coverage to summer 2015, as *Parthenocissus* is deciduous the stems remained but there were no leaves. In July 2016, the mean depth of the foliage on the south wall was 177 ± 92 mm for *Parthenocissus*, 187 ± 25 mm for *Hedera*, and 300 ± 45 mm for *Pileostegia*. There were, however, no statistical differences in the mean foliage depths.

3.3.2 Role of vegetation in summertime weather scenarios

3.3.2.1 External RH during summer 2014

The external RH measured during 'cold day' mornings, between the foliage and external walls of the *Hedera*- and *Parthenocissus*-covered 'buildings' did not differ significantly (Table 3.1). The external RH measured behind the foliage of both the *Hedera*- and *Parthenocissus*-covered buildings, was, however, around 9% RH lower than the RH measured next to bare 'buildings' ($p = 0.033$). This effect was not seen where the cover species was *Pileostegia*, nor was there any significant difference in terms of the external RH between treatments on 'warm day' mornings (Table 3.1).

The RH measured behind the foliage of all treatments during the 'cold day' afternoons were significantly higher than that measured next to bare 'buildings' ($p < .001$). During the 'cold' days' afternoons, the highest external RH was measured behind the *Hedera* foliage, which was 18% RH higher than that measured next to bare 'buildings'. The RHs measured behind the *Pileostegia* and *Parthenocissus* foliage during the 'cold day' afternoons were 6% RH and 8% RH higher, respectively, than those measured next to bare 'buildings'.

During 'warm day' afternoons (Table 3.1), the external RH measured behind the foliage of all vegetated treatments was significantly higher than that measured next to bare 'buildings' ($p < .001$). The RH measured behind the *Hedera* foliage during the 'warm day' afternoons was 28% RH higher than that next to bare 'buildings'. The RH measured behind the *Pileostegia*, and *Parthenocissus* foliage was similar at 7% RH and 8% RH higher respectively, than that measured next to bare 'buildings' on the same days.

The differences between the external RH measured behind the foliage during the mornings and the afternoons were calculated to determine whether vegetation around a building, stabilised RH surrounding the 'building' envelope.

During both the 'cold' and 'warm' days all vegetated treatments significantly reduced variation in the RH external to the 'buildings' ($p < .001$). During the 'cold' days the RH measured behind *Hedera* foliage was 28% RH less variable than that measured next to bare 'buildings' (Table 3.1). On the same days RH measured behind *Pileostegia* and *Parthenocissus* was 10% and 18% RH less variable, compared to that measured next to bare 'buildings'. By comparison, during 'warm' days the RH measured behind the *Hedera* foliage was marginally more stable than when measured on 'cold' days at 32% RH less variable than that measured next to the bare 'buildings' (Table 3.1). Continuing the previously observed trend, the RH measured next to the *Parthenocissus*- and *Pileostegia*-covered 'buildings' was 13% RH and 9% RH less variable respectively.

Table 3.1 Mean ± SD 'external' relative humidity in summer 2014 and the associated LSDs, with four replicates per treatment, except for bare buildings which had three replicates due to sensor malfunction, d.f. = 11: 'Cold' days were when the mean ambient temperature between 14:00 and 17:00 at the High Wycombe MO was < 14 ^{o}C. 'Warm' were days when the mean ambient temperature between 14:00 and 17:00 at the High Wycombe MO was > 23.5 ^{o}C. 'Difference' indicates the difference between the morning and afternoon RH. Numbers in bold are significant (ANOVA, p < 0.05).

Scenario	Cold	Cold	Cold	Warm	Warm	Warm
Time	03:00 - 05:00	14.00 - 17.00	Difference	03:00 - 05:00	14.00 - 17.00	Difference
Ambient external RH (%)	78 ± 7	39 ± 11	39 ± 11	87 ± 7	28 ± 11	59 ± 15
Bare	**89 ± 8**	**39 ± 8**	**51 ± 12**	88 ± 8	**35 ± 15**	**53 ± 16**
Hedera	**80 ± 5**	**57 ± 8**	**23 ± 7**	84 ± 9	**63 ± 18**	**21 ± 16**
Pileostegia	86 ± 4	**45 ± 7**	**41 ± 9**	87 ± 8	**43 ± 15**	**44 ± 16**
Parthenocissus	**80 ± 4**	**47 ± 7**	**33 ± 8**	82 ± 9	**42 ± 14**	**40 ± 16**
P value	**0.033**	**< .001**	**< .001**	0.129	**< .001**	**< .001**
LSD	6.9	5.5	5.3		6.5	8.0

3.3.2.2 External temperature during summer 2014

During both 'cold-' and 'warm day' mornings, temperatures measured behind the foliage of *Hedera*-covered 'buildings' was, 2.8 ^{o}C ($p < .001$) and 1.6 ^{o}C ($p = 0.013$) warmer respectively, than the temperature measured next to the bare 'buildings' (Table 3.2). Temperatures measured behind the foliage of *Pileostegia*- and *Parthenocissus*-covered ‘buildings’ was not, however, significantly warmer than that measured next to bare ‘buildings’ during either scenario.

By comparison, during ‘cold day’ afternoons, temperatures measured behind the foliage of all vegetated treatments were significantly cooler than the temperature measured next to the bare ‘buildings’ ($p < .001$). The temperature measured behind the *Hedera* foliage was 4.7 ^{o}C cooler than the bare ‘buildings’ during the ‘cold day’ afternoons, whereas the temperatures measured behind the *Pileostegia* and *Parthenocissus* foliage were, 1.7 ^{o}C and 1.2 ^{o}C cooler respectively, than temperatures measured next to the bare ‘buildings’ (Table 3.2).

During ‘warm day’ afternoons, however, temperatures measured behind the *Hedera* and *Pileostegia* foliage were, 8.3 ^{o}C and 3.5 ^{o}C cooler respectively, than that measured next to the bare ‘buildings’ ($p < .001$). This trend did not extend to *Parthenocissus*-covered ‘buildings’, the temperature behind whose foliage did not decrease significantly from that found near bare walls (Table 3.2).

During ‘cold’ days, external temperatures measured behind the foliage of all vegetated treatments were significantly less variable than those measured next to bare ‘buildings’ ($p < .001$). The greatest temperature stabilisation occurred behind *Hedera* foliage, which produced conditions on average 7 ^{o}C less variable per day than those measured next to bare ‘buildings’. Meanwhile temperatures measured behind the *Parthenocissus* and *Pileostegia* foliage averaged 2.2 ^{o}C less variable per day than the temperatures measured next to the bare ‘buildings’ (Table 3.2).

During ‘warm’ days, external temperatures measured behind the foliage of *Hedera*- and *Pileostegia*-covered ‘buildings’ were significantly less variable than the temperatures measured next to bare ‘buildings’ ($p < .001$). As per ‘cold’ days, the greatest temperature stabilisation occurred behind the *Hedera* foliage at an average of 9.8 ^{o}C less variable per day than those measured next to bare ‘buildings’. Meanwhile the temperatures measured behind *Pileostegia* foliage were 3.9 ^{o}C less variable per day than the temperatures measured next to the bare ‘buildings’ (Table 3.2). Lastly, the temperatures measured behind the *Parthenocissus* foliage were not significantly less variable than the temperatures measured next to the bare ‘buildings’.

Table 3.2 Mean ± SD 'external' temperature in summer 2014 and the associated LSDs, with four replicates per treatment, d.f. = 12: 'Cold' days were when the mean ambient temperature between 14:00 and 17:00 at the High Wycombe MO was < 14 °C. 'Warm' were days when the mean ambient temperature between 14:00 and 17:00 at the High Wycombe MO was > 23.5 °C. 'Difference' indicates the difference between the afternoon and morning temperatures. Numbers in bold are significant (ANOVA, p < 0.05).

Scenario	Cold	Cold	Cold	Warm	Warm	Warm
Time	03:00 - 05:00	14:00 - 17:00	Difference	03:00 - 05:00	14:00 - 17:00	Difference
Ambient external temperature (°C)	7.8±0.7	13.4 ± 0.4	5.6 ± 0.9	16.2 ± 1.5	24.7±0.7	8.5 ± 1.8
Bare	**8.4 ± 1.3**	**20.9 ± 2.2**	**12.5 ± 2.7**	**16.6 ± 1.3**	**34.8 ± 4.7**	**18.2 ± 4.5**
Hedera	**11.2 ± 1.4**	**16.7 ± 1.4**	**5.5 ± 2.3**	**18.2 ± 1.1**	**26.5 ± 3.9**	**8.4 ± 4.5**
Pileostegia	9.0 ± 1.2	**19.2 ± 1.5**	**10.3 ± 2.0**	17.0 ± 1.1	**31.3 ± 3.7**	**14.3 ± 3.7**
Parthenocissus	9.4 ± 1.2	**19.7 ± 1.9**	**10.3 ± 2.4**	17.2 ± 1.1	32.5 ± 4.1	15.3 ± 4.2
P value	**< .001**	**< .001**	**< .001**	**0.013**	**< .001**	**< .001**
LSD	1.05	1.10	1.84	0.89	2.52	3.06

3.3.2.3 Internal temperature during summer 2014

During 'cold day' mornings, the temperatures measured inside *Pileostegia*- and *Parthenocissus*-covered 'buildings' were, 3.0 °C and 3.5 °C warmer respectively, than those measured inside bare 'buildings' (p = 0.048; Table 3.3). During the 'cold day' mornings there were, however, no significant differences between the temperatures measured inside the *Hedera*-covered 'buildings' and those measured inside bare 'buildings'.

During 'warm day' mornings there were no significant differences between temperatures measured inside vegetated 'buildings' and temperatures measured inside bare 'buildings'.

During both 'cold-' and 'warm day' afternoons, temperatures measured inside the foliage-covered 'buildings' were all significantly cooler than those measured inside the bare 'buildings' (p < .001), the effect was most pronounced on 'warm day' afternoons. The greatest reductions in temperature occurred in *Hedera*-covered 'buildings' (6.5/4.5 °C cooler on 'warm/cold day' afternoons), followed by *Parthenocissus*- (4.5/3.2 °C) and the *Pileostegia*-covered (3.8/2.1 °C) 'buildings' (Table 3.3).

During both the 'cold' and 'warm' days the daily temperatures measured inside the vegetated 'buildings' were less variable than the daily temperatures measured inside the bare 'buildings' (least variable *Parthenocissus* < *Hedera* < *Pileostegia*; Table 3.3), though effects did not differ significantly between 'warm' and 'cold' days. Temperatures measured inside the *Parthenocissus*-covered 'buildings' were 6.2-6.7 °C less variable daily than the temperatures measured inside the bare 'buildings' (p = 0.003 for cold days, p = 0.028 for warm days) and those measured inside the *Hedera*- and *Pileostegia*-covered 'buildings' were 5.7 °C and 5.1-5.2°C less variable respectively (Table 3.3).

Table 3.3 Mean ± SD 'internal' temperature in summer 2014 and the associated LSDs with four replicates per treatment, d.f. = 12: 'Cold' days were when the mean ambient temperature between 14:00 and 17:00 at the High Wycombe MO was < 14 °C. 'Warm' were days when the mean ambient temperature between 14:00 and 17:00 at the High Wycombe MO was > 23.5 °C. 'Difference' indicates the difference between the afternoon and morning temperatures. Numbers in bold are significant (ANOVA, p < 0.05).

Scenario	Cold	Cold	Cold	Warm	Warm	Warm
Time	03:00 - 05:00	14:00 - 17:00	Difference	03:00 - 05:00	14:00 - 17:00	Difference
Ambient external temperature (°C)	7.8 ± 0.7	13.4 ± 0.4	5.6 ± 0.9	16.2 ± 1.5	24.7 ± 0.7	8.5 ± 1.8
Bare	**10.5 ± 2.4**	**20.6 ± 1.7**	**10.1 ± 2.9**	20.1 ± 2.5	**31.8 ± 3.6**	**11.7 ± 4.7**
Hedera	11.7 ± 2.3	**16.1 ± 1.3**	**4.4 ± 3.3**	19.2 ± 2.1	**25.3 ± 2.5**	**6.0 ± 4.0**
Pileostegia	**13.5 ± 0.9**	**18.5 ± 0.7**	**5.0 ± 1.2**	21.5 ± 0.8	**28.0 ± 1.7**	**6.5 ± 2.3**
Parthenocissus	**14.0 ± 0.7**	**17.4 ± 0.5**	**3.4 ± 0.8**	21.8 ± 0.7	**27.3 ± 1.6**	**5.5 ± 2.1**
P value	**0.048**	**< .001**	**0.003**	0.154	**< .001**	**0.028**
LSD	2.62	0.97	3.24		1.97	4.26

3.3.2.4 External RH during summer 2015

During 'cold-' and 'warm day' mornings the external RH measured behind the foliage of vegetated 'buildings' was not significantly different from the RH measured next to bare 'buildings' (Table 3.4). Nor was that measured on 'cold day' afternoons, at 9% RH higher (p = 0.06, LSD 7.5). There was also, no significant increase in the RH measured behind the foliage of the *Pileostegia*- and *Parthenocissus*-covered 'buildings' compared to the bare 'buildings' in either temperature scenario (Table 3.4)

During 'warm day' afternoons, however, the external RH measured behind *Hedera* foliage was 11% RH (p = 0.033) higher than that measured next to bare 'buildings'. All vegetated treatments significantly reduced the daily variation in the external RH in all temperature scenarios, compared to that measured next to bare 'buildings'. In both scenarios the *Hedera* foliage produced the greatest reduction in daily variation compared to bare 'buildings', by 10% and 11% RH on 'cold' (p < .001) and 'warm' (p = 0.008) days respectively, followed by *Parthenocissus* (6% RH on 'cold' days, 7% RH on 'warm') and *Pileostegia* (5% RH on 'cold' days and 6% RH on 'warm'). The level of variation in RH did not appear to be significantly different between 'warm' and 'cold' days (Table 3.4).

Table 3.4 Mean ± SD 'external' relative humidity in summer 2015 and the associated LSDs with three replicates per treatment, d.f. = 8: 'Cold' days were when the mean ambient temperature between 14:00 and 17:00 at the UoR MO was < 19 °C. 'Warm' days were when the mean ambient temperature between 14:00 and 17:00 at the UoR MO was > 23 °C. 'Difference' indicates the difference between the morning and afternoon RH. Numbers in bold are significant (ANOVA, p < 0.05).

Scenario	Cold	Cold	Cold	Warm	Warm	Warm
Time	03:00 - 05:00	14.00 - 17.00	Difference	03:00 - 05:00	14.00 - 17.00	Difference
Ambient external RH (%)	91 ± 3	71 ± 11	20 ± 10	88 ± 10	45 ± 11	43 ± 13
Bare	85 ± 9	62 ± 14	**23 ± 11**	85 ± 7	**36 ± 10**	**48 ± 14**
Hedera	84 ± 8	71 ± 15	**13 ± 9**	84 ± 4	**47 ± 11**	**37 ± 10**
Pileostegia	85 ± 8	67 ± 14	**18 ± 9**	84 ± 6	42 ± 10	**42 ± 12**
Parthenocissus	79 ± 10	62 ± 15	**17 ± 9**	78 ± 7	37 ± 12	**41 ± 11**
P value	0.228	0.06	**< .001**	0.231	**0.033**	**0.008**
LSD		7.5	3.0		7.5	5.5

3.3.2.5 Internal RH during summer 2015

There was no significant effect of plant treatment on the internal measurements of RH, regardless of temperature scenario in the mornings (p = 0.085 and p = 0.06 'cold-' and 'warm day' mornings respectively; Table 3.5). This was also true on 'cold day' afternoons (p = 0.189; Table 3.5). During the 'warm day' afternoons, however, the RH measured inside *Hedera*-covered 'buildings' was 17% RH higher than that measured inside bare 'buildings'; lesser, but also significant, effects were detected for *Pileostegia*- (9%) and *Parthenocissus*-covered (12%) 'buildings' (p = 0.011, Table 3.5).

Daily variation in internal RH during this period was rather more complex. During 'cold' days the daily variation in internal RH was reduced by 4% RH in the *Hedera*-covered 'buildings' compared to bare 'buildings', though there was no significant equivalent reduction recorded for the other species (p = 0.04). Conversely during 'warm' days, daily variation in internal RH was lowest for bare 'buildings' (5.1% RH less than *Hedera* or *Parthenocissus* treatments, 6.7% RH less than *Pileostegia;* p < .001; Table 3.5).

Table 3.5 Mean ± SD 'internal' relative humidity in summer 2015 and the associated LSDs with three replicates per treatment, except for *Parthenocissus*-covered buildings which had two replicates due to sensor malfunction d.f. = 7: 'Cold' days were when the mean ambient temperature between 14:00 and 17:00 at the UoR MO was < 19 °C. 'Warm' days were when the mean ambient temperature between 14:00 and 17:00 at the UoR MO was > 23 °C. 'Difference' indicates the difference between the morning and afternoon RH. Numbers in bold are significant (ANOVA, p < 0.05).

Scenario	Cold	Cold	Cold	Warm	Warm	Warm
Time	03:00 - 05:00	14.00 - 17.00	Difference	03:00 - 05:00	14.00 - 17.00	Difference
Ambient external RH (%)	91 ± 3	71 ± 11	20 ± 10	88 ± 10	45 ± 11	43 ± 13
Bare	53 ± 5	63 ± 5	**10 ± 3**	54 ± 5	**57 ± 9**	**2.4 ± 5.4**
Hedera	65 ± 5	71 ± 4	**6 ± 2**	67 ± 5	**74 ± 4**	**7.5 ± 1.2**
Pileostegia	54 ± 7	63 ± 6	9 ± 3	57 ± 7	**66 ± 6**	**9.1 ± 3.4**
Parthenocissus	59 ± 4	68 ± 2	9 ± 3	62 ± 3	**69 ± 3**	**7.6 ± 1.9**
P value	0.085	0.189	**0.04**	0.06	**0.011**	**< .001**
LSD	9.8		2.7	9.3	8.6	1.59

3.3.2.6 External temperature during summer 2015

External temperatures measured during 'cold day' mornings, behind the foliage of both the *Hedera*- and *Parthenocissus*-covered 'buildings', were significantly (at least 1.2 °C) warmer than those measured next to bare 'buildings' ($p = 0.014$; Table 3.6). During the 'warm day' mornings, however, only the temperature measured behind the *Hedera* foliage was warmer (by 2.6 °C), with no significant temperature difference observed behind *Parthenocissus* ($p = 0.071$; Table 3.6). The temperatures measured behind *Pileostegia* foliage were not significantly warmer than those measured next to bare 'buildings' in either temperature scenario.

During both 'cold' and 'warm day' afternoons, temperatures measured behind the foliage of the vegetated treatments were significantly cooler than those next to bare 'buildings' ($p < .001$). While effects were more pronounced on 'warm' days, the greatest cooling effect occurred behind the *Hedera* (2.2/5.7 °C cooler on 'cold'/'warm' days) foliage followed by *Pileostegia* (1.4/4.6 °C cooler) then *Parthenocissus* (1.2/3.4 °C cooler) as compared to bare 'buildings' ($p < .001$; Table 3.6).

During 'cold' and 'warm' days, all the vegetated treatments significantly reduced the daily variation in external temperature around 'building' envelopes, compared to the daily variation measured next to bare 'buildings' ($p < .001$; Table 3.6). In both cases, the greatest stabilisation was produced by *Hedera* (3.2 °C less variation on average on 'cold' days, 8.3 °C less on 'warm' days). The effects of other species on external temperature stability, whilst not as great as those produced by *Hedera*, vary based on the temperature scenario: on 'cold' days, variation was much lower behind *Parthenocissus* than *Pileostegia* (a reduction of 2.4 °C vs. 1.7 °C when compared to bare 'buildings'), but on 'warm' days the difference in effects produced by the two species is all but non-existent (a 4.9 °C reduction for *Parthenocissus*, 5.1 °C for *Pileostegia*; a reversal in order, but very slight).

Table 3.6 Mean ± SD 'external' temperature in summer 2015 and the associated LSDs with three replicates per treatment, d.f. = 8: 'Cold' days were when the mean ambient temperature between 14:00 and 17:00 at the UoR MO was < 19 °C. 'Warm' days were when the mean ambient temperature between 14:00 and 17:00 at the UoR MO was > 23 °C. 'Difference' indicates the difference between the afternoon and morning temperatures. Numbers in bold are significant (ANOVA, p < 0.05).

Scenario	Cold	Cold	Cold	Warm	Warm	Warm
Time	03:00 - 05:00	14:00 - 17:00	Difference	03:00 - 05:00	14:00 - 17:00	Difference
Ambient external temperature (°C)	14.0 ± 1.3	18.7 ± 0.1	4.7 ± 1.3	14.4 ± 3.4	26.1 ± 3.6	11.7 ± 4.1
Bare	**15.0 ± 0.8**	**22.2 ± 2.1**	**7.1 ± 2.8**	14.7 ± 2.8	**32.6 ± 3.6**	**17.9 ± 4.0**
Hedera	**16.2 ± 0.9**	**20.0 ± 1.5**	**3.9 ± 2.0**	17.3 ± 5.4	**26.9 ± 2.8**	**9.6 ± 5.2**
Pileostegia	15.4 ± 0.8	**20.8 ± 1.6**	**5.4 ± 2.1**	15.2 ± 2.7	**28.0 ± 3.4**	**12.8 ± 3.7**
Parthenocissus	**16.3 ± 0.7**	**21.0 ± 1.7**	**4.7 ± 2.0**	16.2 ± 2.4	**29.2 ± 3.2**	**13.0 ± 3.2**
P value	**0.014**	**< .001**	**< .001**	0.071	**< .001**	**< .001**
LSD	0.78	0.29	0.95	2.06	1.81	2.80

3.3.2.7 Internal temperatures during summer 2015

During the 'cold-' and 'warm day' mornings, there were no significant differences between temperatures measured inside any 'buildings' regardless of whether they had been vegetated or remained bare. Potential causes for and significance of this finding will be covered in the discussion. During both 'warm-' and 'cold day' afternoon scenarios, however, *Hedera*-covered 'buildings' displayed a significant reduction in internal temperature compared to bare 'buildings'. During 'cold day' afternoons the temperature measured inside *Hedera*-covered buildings was 3.1 °C cooler than the temperature measured inside the bare 'buildings', whereas the same treatment produced a 7.2 °C cooling effect over bare 'buildings' on 'warm day' afternoons ($p < .001$; Table 3.7). By comparison, both the *Pileostegia* and *Parthenocissus* foliage (there is no discernible difference in effect between the species in this case) produce lesser cooling effects of 2.2 °C and 4.9 °C on 'cold-' and 'warm day' afternoons respectively, compared to the bare 'buildings' ($p < .001$).

During both the 'cold' and 'warm' days the daily variation in internal temperature was significantly reduced in all vegetated treatments compared to the bare 'buildings' ($p < .001$; Table 3.7). The greatest reduction in daily internal temperature variation occurred inside the *Hedera* covered buildings (3.4 °C less variable on 'cold' days/7.4 °C on 'warm' days), followed by the *Parthenocissus*- (2.8 °C/5.6 °C) and *Pileostegia*-covered (2.5 °C/5.3 °C) 'buildings' ($p < .001$; Table 3.7).

Table 3.7 Mean ± SD 'internal' temperature in summer 2015 and the associated LSDs with three replicates per treatment, d.f. = 8: 'Cold' days were when the mean ambient temperature between 14:00 and 17:00 at the UoR MO was < 19 °C. 'Warm' days were when the mean ambient temperature between 14:00 and 17:00 at the UoR MO was > 23 °C. 'Difference' indicates the difference between the afternoon and morning temperatures. Numbers in bold are significant (ANOVA, p < 0.05).

Scenario	Cold	Cold	Cold	Warm	Warm	Warm
Time	03:00 - 05:00	14:00 - 17:00	Difference	03:00 - 05:00	14:00 - 17:00	Difference
Ambient external temperature (°C)	14.0 ± 1.3	18.7 ± 0.1	4.7 ± 1.3	14.4 ± 3.4	26.1 ± 3.6	11.7 ± 4.1
Bare	18.5 ± 1.2	**22.2 ± 1.9**	**4.1 ± 1.9**	18.9 ± 2.6	**31.0 ± 3.8**	**13.0 ± 3.2**
Hedera	18.6 ± 1.1	**19.1 ± 0.8**	**0.7 ± 0.9**	18.9 ± 2.1	**23.8 ± 2.8**	**5.6 ± 2.1**
Pileostegia	18.5 ± 1.1	**20.0 ± 1.1**	**1.6 ± 1.2**	18.9 ± 2.4	**26.1 ± 3.2**	**7.7 ± 2.4**
Parthenocissus	18.7 ± 1.1	**20.0 ± 1.0**	**1.3 ± 1.0**	19.1 ± 2.3	**26.1 ± 3.3**	**7.4 ± 2.6**
P value	0.438	**< .001**	**< .001**	0.617	**< .001**	**< .001**
LSD		0.57	0.64		1.57	1.70

3.3.2.8 Substrate moisture and plant photosynthesis rates during summer

The soil associated with *Parthenocissus* and *Pileostegia* plants was significantly drier than that under *Hedera* foliage (Table 3.8), the latter of which was closer in SMC to the soil next to the bare buildings (0.31 ± 0.06 m^3m^{-3}). This may be because the soil by the bare 'buildings' was covered by Mypex®, reducing evaporative losses, in a similar manner to ground cover by *Hedera* foliage. Despite this difference in SMC between *Parthenocissus*, *Hedera* and *Pileostegia*, the SMC remained near 'well-watered' (> 0.20 m^3m^{-3}; Blanuša et al. (2013)) and there were no significant differences in the assimilation rates (A), leaf stomatal conductances (g_s), and wall leaf area indexes (WLAI) of the three studied species on at the time of the measurements (Table 3.8). Details of measurements made can be found in Chapter 2, sections 2.5.1 and 2.5.2.

Table 3.8 Mean ± SD soil moisture content (SMC), leaf stomatal conductance (g_s), net carbon dioxide assimilation rate (A), and wall leaf area index (WLAI) of the studied plants *in situ* and the associated LSDs with three replicates per treatment, d.f. = 6. Measurements made on 17th July 2015, except WLAI which was made on 1st September 2015 (ANOVA, p < 0.05).

	SMC (m^3m^{-3})	g_s ($molm^{-2}s^{-1}$)	A ($\mu molm^{-2}s^{-1}$)	WLAI
Hedera	0.32 ± 0.02	0.11 ± 0.05	7.3 ± 2.0	4.0 ± 1.2
Pileostegia	0.19 ± 0.09	0.06 ± 0.02	6.0 ± 1.1	2.5 ± 0.9
Parthenocissus	0.21 ± 0.06	0.08 ± 0.02	7.3 ± 1.5	4.2 ± 1.2
P value	0.01	0.24	0.545	0.214
LSD	0.072			

3.3.3 Role of vegetation in spring and winter weather scenarios

3.3.3.1 External RH during spring 2015

There were no significant differences between RH as measured next to bare 'buildings' compared to the RH measured behind the *Hedera* foliage (Table 3.9).

Table 3.9 Mean ± SD 'external' relative humidity during spring 2015 with three replicates per treatment, d.f. = 4: 'Cold' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was ≤ 3 °C. 'Warm' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was > 7 °C, (ANOVA, $p < 0.05$).

Scenario	Cold	Cold	Warm	Warm
Time	05.00-07.00	14.00-17.00	05.00-07.00	14.00-17.00
Ambient external RH (%)	97 ± 2	66 ± 17	78 ± 10	56 ± 24
Bare	94 ± 4	61 ± 16	79 ± 9	54 ± 22
Hedera	85 ± 7	56 ± 17	74 ± 10	49 ± 22
P value	0.153	0.276	0.307	0.257

3.3.3.2 Internal RH during spring 2015

There were no significant differences between the RH measured by internal south walls of *Hedera*-covered 'buildings' and bare 'buildings' (Table 3.10).

Table 3.10 Mean ± SD 'internal' relative humidity during spring 2015 with three replicates for *Hedera*-covered buildings and due to sensor malfunction two replicates for bare buildings, d.f. = 3: 'Cold' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was ≤ 3 °C. 'Warm' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was > 7 °C, (ANOVA, $p < 0.05$).

Scenario	Cold	Cold	Warm	Warm
Time	05.00 - 07.00	14.00 - 17.00	05.00 - 07.00	14.00 - 17.00
Ambient external RH (%)	97 ± 2	66 ± 17	78 ± 10	56 ± 24
Bare	63 ± 6	71 ± 10	69 ± 4	70 ± 12
Hedera	67 ± 8	72 ± 9	73 ± 6	76 ± 6
P value	0.519	0.884	0.46	0.503

3.3.3.3 External wall temperature during spring 2015

The only significant difference between temperatures measured next to external south walls occurred during 'cold day' mornings, where temperatures measured behind the *Hedera* foliage was 0.4 °C warmer than that measured next to the bare buildings' ($p = 0.01$; Table 3.11).

Table 3.11 Mean ± SD 'external' temperature during spring 2015 and the associated LSDs with three replicates per treatment, d.f. = 4: 'Cold' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was ≤ 3 ^{o}C. 'Warm' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was > 7 ^{o}C. Numbers in bold are significant (ANOVA, p < 0.05).

Scenario	Cold	Cold	Warm	Warm
Time	05.00 - 07.00	14.00 - 17.00	05.00 - 07.00	14.00 - 17.00
Ambient external temperature (^{o}C)	1.7 ± 1.0	9.3 ± 1.1	7.5 ± 0.5	11.6 ± 1.0
Bare	**1.7 ± 1.0**	11.1 ± 1.3	7.3 ± 0.5	12.6 ± 1.6
Hedera	**2.1 ± 1.0**	11.5 ± 1.4	7.4 ± 0.6	12.9 ± 1.7
P value	**0.01**	0.242	0.114	0.484
LSD	0.28			

3.3.3.4 Internal temperature during spring 2015

There were no significant differences between temperatures measured inside *Hedera*-covered 'buildings' and bare 'buildings' on either the 'cold' or 'warm' days' mornings (Table 3.12). Effects did, however, become evident during the afternoons of both temperature scenarios. During 'cold day' afternoons temperatures measured inside *Hedera*-covered 'buildings' were significantly 1.7 ^{o}C cooler than those measured inside the bare 'buildings' (p = 0.005). During the 'warm day' afternoons the temperature measured inside the *Hedera*-covered 'buildings' was 1.2 ^{o}C cooler than the internal temperature of the bare 'buildings' (p = 0.042; Table 3.12).

Table 3.12 Mean ± SD 'internal' temperature during spring 2015 and the associated LSDs with three replicates for *Hedera*-covered buildings and due to sensor malfunction two replicates for bare buildings, d.f. = 3: 'Cold' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was ≤ 3 ^{o}C. 'Warm' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was > 7^{o}C. Numbers in bold are significant (ANOVA, p < 0.05).

Scenario	Cold	Cold	Warm	Warm
Time	05.00-07.00	14.00-17.00	05.00-07.00	14.00-17.00
Ambient external temperature (^{o}C)	1.7 ± 1.0	9.3 ± 1.1	7.5 ± 0.5	11.6 ± 1.0
Bare	8.0 ± 1.2	**16.1 ± 2.1**	11.1 ± 1.4	**17.0 ± 2.3**
Hedera	8.5 ± 1.0	**14.4 ± 1.5**	11.4 ± 1.1	**15.8 ± 1.6**
P value	0.217	**0.005**	0.178	**0.042**
LSD		0.7		1.17

3.3.3.5 Winter 2016

While species other than *Hedera* were tested (*Pileostegia* and *Parthenocissus*; see Chapter 2, section 2.10 experiment 2) they have been excluded from this analysis as there were no significant differences in any measured parameter between the *Pileostegia* or *Parthenocissus* data and that acquired from bare 'buildings'(p > 0.05).

3.3.3.6 External RH during winter 2016

The only significant increase in RH occurred on ‘warm day’ afternoons during which heating had been implemented. In this situation the RH measured behind the *Hedera* foliage was 3.7% RH higher than that measured by the bare ‘buildings’ ($p = 0.027$; Table 3.13).

Table 3.13 Mean ± SD ‘external’ relative humidity during winter 2016 and the associated LSDs, with three replicates per treatment, d.f. = 4: ‘Cold’ days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was ≤ 3 °C. ‘Warm’ days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was > 9 °C. Unheated (UH), heated (H). Unheated and heated days occurred on different days. Numbers in bold are significant (ANOVA, p < 0.05).

Scenario	Cold (UH)	Cold (UH)	Cold (H)	Cold (H)	Warm (H)	Warm (H)
Time	05.00 - 07.00	14.00 - 17.00	05.00 - 07.00	14.00 - 17.00	05.00 - 07.00	14.00 - 17.00
Ambient external RH (%)	92.3 ± 7.6	81.1 ± 10.9	91.9 ± 8.6	62.7 ± 9.9	86.5 ± 11.0	81.8 ± 10.6
Bare	90.0 ± 6.0	80.0 ± 10.7	88.9 ± 5.9	65.5 ± 4.8	88.2 ± 9.5	**81.8 ± 8.4**
Hedera	85.3 ± 4.8	79.7 ± 10.0	83.6 ± 5.4	67.6 ± 5.1	89.9 ± 8.2	**85.5 ± 8.4**
P value	0.068	0.868	0.098	0.336	0.184	**0.027**
LSD	5.23		6.86			2.97

3.3.3.7 Internal RH during winter 2016

In all scenarios the RH measured inside *Hedera*-covered ‘buildings’ was lower than the internal RH of bare ‘buildings’ though this difference was not always significant. Heating appears to have variable bearing on this effect. During ‘cold day’ unheated afternoons the internal RH of *Hedera*-covered ‘buildings’ was 8.1% RH less than that measured inside bare ‘buildings’ ($p = 0.023$), but the addition of heating to the same situation produced only a 0.2% RH further decrease to 8.3% RH ($p = 0.032$). Comparatively, during the ‘warm day’ mornings on which heating had been implemented, the internal RH of the *Hedera*-covered ‘buildings’ was 5.3% RH less than that inside the bare ‘buildings’($p = 0.048$), while unheated *Hedera*-clad buildings maintained the same level of RH (Table 3.14).

Table 3.14 Mean ± SD ‘internal’ relative humidity during winter 2016 and the associated LSDs, with three replicates per treatment, d.f. = 4: ‘Cold’ days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was ≤ 3 °C. ‘Warm’ days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was > 9 °C. Unheated (UH), heated (H). Unheated and heated days occurred on different days. Numbers in bold are significant (ANOVA, p < 0.05).

Scenario	Cold (UH)	Cold (UH)	Cold (H)	Cold (H)	Warm (H)	Warm (H)
Time	05.00 - 07.00	14.00 - 17.00	05.00 - 07.00	14.00 - 17.00	05.00 - 07.00	14.00 - 17.00
Ambient external RH (%)	92.3 ± 7.6	81.1 ± 10.9	91.9 ± 8.6	62.7 ± 9.9	86.5 ± 11.0	81.8 ± 10.6
Bare	94.5 ± 3.3	**96.7 ± 2.7**	83.3 ± 6.3	**89.0 ± 6.8**	**90.6 ± 7.1**	92.8 ± 6.8
Hedera	86.6 ± 2.9	**88.6 ± 2.6**	77.9 ± 4.9	**80.7 ± 4.1**	**85.3 ± 5.0**	87.1 ± 4.9
P value	0.051	**0.023**	0.081	**0.032**	**0.048**	0.052
LSD	8.00	6.17	6.41	7.13	5.20	5.74

3.3.3.8 External wall temperature during winter 2016

During 'cold day' mornings, temperatures measured behind *Hedera* foliage were 0.4 ^{o}C (for unheated buildings; p = 0.004) and 1 ^{o}C (for heated buildings, p = 0.009) warmer than those measured next to bare 'buildings'. During 'warm day' mornings, temperatures measured behind *Hedera* foliage were 0.4 ^{o}C lower than that measured next to bare 'buildings' (p = 0.001). During the 'warm day' afternoons temperatures measured behind *Hedera* foliage were 0.8 ^{o}C lower than those measured next to bare 'buildings' (p < .001; Table 3.15).

Table 3.15 Mean ± SD 'external' temperature during winter 2016 and the associated LSDs, with three replicates per treatment, d.f. = 4: 'Cold' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was ≤ 3 ^{o}C. 'Warm' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was > 9 ^{o}C. Unheated (UH), heated (H). Unheated and heated days occurred on different days. Numbers in bold significant (ANOVA, p < 0.05).

Scenario	Cold (UH)	Cold (UH)	Cold (H)	Cold (H)	Warm (H)	Warm (H)
Time	05.00 - 07.00	14.00 - 17.00	05.00 - 07.00	14.00 - 17.00	05.00 - 07.00	14.00 - 17.00
Ambient external temperature (^{o}C)	0.5 ± 1.0	3.5 ± 0.3	-0.8 ± 3.7	6.0 ± 2.6	10.8 ± 1.0	12.7 ± 0.8
Bare	**0.6 ± 0.6**	3.6 ± 0.5	**-0.4 ± 2.5**	5.9 ± 2.7	**10.3 ± 1.1**	**12.8 ± 0.7**
Hedera	**1.0 ± 0.2**	3.4 ± 0.5	**0.6 ± 2.1**	5.5 ± 2.5	**9.9 ± 1.0**	**12.0 ± 0.6**
P value	**0.004**	0.066	**0.009**	0.058	**0.001**	**<.001**
LSD	0.21	0.24	0.61	0.39	0.15	0.21

3.3.3.9 Internal temperature during winter 2016

During 'cold day' mornings, temperatures measured inside the unheated *Hedera*-covered 'buildings' were 1.3 ^{o}C warmer than those measured inside the bare 'buildings' (p = 0.002). Once heaters were installed temperatures measured inside *Hedera*-covered 'buildings' increased to 2.2 ^{o}C warmer than those measured inside bare 'buildings' (p < .001). There were no significant differences between the temperatures measured inside the bare 'buildings' and *Hedera*-covered 'buildings' during either afternoons or 'warm day' mornings during which heating had been implemented (Table 3.16).

Table 3.16 Mean ± SD 'internal' temperature during winter 2016 and the associated LSDs, with three replicates per treatment, d.f. = 4: 'Cold' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was ≤ 3 °C. 'Warm' days were when the mean ambient temperature between 05:00 and 07:00 at the UoR MO was > 9 °C. Unheated (UH), heated (H). Unheated and heated days occurred on different days. Numbers in bold are significant (ANOVA, $p < 0.05$).

Scenario	Cold (UH)	Cold (UH)	Cold (H)	Cold (H)	Warm (H)	Warm (H)
Time	05.00 - 07.00	14.00 - 17.00	05.00 - 07.00	14.00 - 17.00	05.00 - 07.00	14.00 - 17.00
Ambient external temperature (°C)	0.5 ± 1.0	3.5 ± 0.3	-0.8 ± 3.7	6.0 ± 2.6	10.8 ± 1.0	12.7 ± 0.8
Bare	**1.0 ± 0.6**	3.2 ± 1.0	**3.9 ± 2.6**	8.0 ± 3.0	11.4 ± 2.0	13.6 ± 2.5
Hedera	**2.3 ± 0.2**	3.1 ± 0.7	**6.1 ± 2.2**	8.0 ± 2.2	11.5 ± 1.7	12.7 ± 2.1
P value	**0.002**	0.827	**< .001**	0.988	0.738	0.146
LSD	0.50		0.64			

3.4 Discussion

The most important outcome of this experiment was that refined and robustly replicated data was added to the already significant body of work showing that *Hedera* and the other tested species reduce peak internal and external building temperatures by at least 1 °C in summer, due to cooling by shading and evapotranspiration, as per hypothesis one (Pérez et al., 2011a, Ottelé and Perini, 2017, Perini et al., 2017a). This was a similar reduction in temperature to the findings of Cameron et al. (2014) and Perini et al. (2011a). Furthermore, all tested species displayed an ability to stabilise temperature as per hypothesis two, reducing the temperature range, internally and externally by at least 3 °C in summer, which was similar to the stabilisation effects found by Sternberg et al. (2011a). It is hoped that this will add to the already substantial support for urban greening schemes.

The findings concerning RH and potential insulating properties of *Hedera* were, however, more variable. During the afternoons (in both summer and winter) the external RH mostly appeared to be higher behind *Hedera* foliage. In summer this effect appears to largely result from evapotranspiration, whereas in cooler seasons the foliage may trap water vapour from rain or low levels of evapotranspiration. However, impacts on RH were more pronounced for *Hedera* (an increase of at least 9% RH during the summer afternoons, as per hypothesis three), than the other plant species tested which produced smaller similar impacts on RH around the 'buildings'. The effect of vegetation on the internal RH depends largely on the climatic circumstances; in summer (during both mornings and afternoons), the RH increased inside the 'buildings' of most tested species (though *Pileostegia* produced the least increase). The effect of the *Hedera*-covering on internal RH in early spring and winter was more variable, and is likely to be due to interactions between the heaters heating the air (and reducing the relative humidity, if not the absolute humidity) and a difference in coverage between the two years. However, in winter 2016, when the wall coverage was greater (89 ± 6%) the RH inside the *Hedera*-covered buildings was lower than the RH measured inside the bare 'buildings' during both mornings and afternoons. This may be due to a combination of slightly warmer temperatures inside the *Hedera*-covered buildings and slightly reduced external RH behind the *Hedera* foliage, though this requires further research to elucidate the causes.

Interestingly, there was a strong but mostly non-significant trend for the external RH measured behind the foliage of all species to be lower than that of the bare buildings during the nights/mornings throughout both seasons and years, which may indicate that the slight increase in air temperature due to the insulation effects of the foliage was sufficient to maintain the lower RH. No comparable studies have been found within the literature, glimpses of similar effects are reported (Miller et al., 2007, Ottelé, 2011), but as they were not the focus of the studies, an explanation for the effect was not given. Miller et al. (2007) measured the temperature and RH behind the foliage of their bioshaders, however, the results were not reported. A reduction in RH was reported inside the room for some nights, with the greatest decrease in RH occurring inside the plant covered room in October, by which time the plants monitored (*Parthenocissus quinquefolia*) would have been starting to senesce. Therefore reductions in RH at this point may have been due to precipitation interception compared to the bare windows, though the effects were not discussed. Ottelé (2011) also monitored RH behind foliage (albeit in a controlled environment), -5 ^{o}C was used as the winter temperature and an initial reduction in external RH over the first 12 hours was reported, though this may have been due to RH equalisation between the external and internal environments as wall cavity RH increased over the same time.

The relatively high RH behind *Hedera* foliage is not, however, expected to particularly represent an issue practically for the following reasons. Firstly, *Hedera's* protective effect from driving rain may counteract some of the impact on external RH derived from its tendency to trap water vapour. Moreover, it is believed that a well-constructed and maintained building (including cavity walls and modern cement work) would prove resistant to internal increases in RH, though this requires further research. Therefore, *Hedera*-based schemes, and direct greening in general, could prove very successful where installed with consideration of building integrity and the local climate. For example, it might prove beneficial to green walls particularly affected by driving rain, and leverage the benefits of precipitation interception by foliage.

Furthermore, as others have found (Perini et al., 2011a, Bolton et al., 2014), the insulation effects of direct greening are minimal at intermediate temperatures, though they do improve as temperatures reach extremes. It is believed that this may be a side effect of the shading provided by plants used in greening, which artificially reduces temperatures (especially at the southern aspect) by inhibiting solar gains, as was also found by in a simulation of vertical greening (Carlos, 2015). It may, therefore be advisable to prune evergreen species (such as *Hedera*) in autumn to avoid this problem, or use a deciduous species such as *Parthenocissus* (or any of the species in Chapter 1, section 1.1 Table 1.1 or other climbing species suitable to the site). Pruning may also improve insulation against wind and rain by increasing foliage density in the following year (McAllister and Marshall, 2017).

In addition, the insulating effects found externally (up to 2.8 ^{o}C warmer for the *Hedera*-covering) did not appear to translate to the internal environment over summer, unlike *Parthenocissus* and *Pileostegia*, where there was an indication of night-time warming due to the foliage. It is believed that this effect, in the case of *Hedera,* may be due to a lag in the heat transfer between the building envelope and the internal environment. Therefore, the temperature increase behind the foliage derived from night-time insulation (as per hypothesis four) does not translate to the internal environment until the daytime, when it is overwhelmed by the much larger increases from summer solar gains. It is beneficial that the presence of *Hedera* does not increase the internal building temperature at night during the summer, as this is a cause of thermal discomfort during hot summers and in cities suffering from the urban heat island effect.

In winter, however, the same insulation effects and resulting increase in external temperature did translate to an increase in internal temperatures (by up to 2 ^{o}C (in the mornings) for *Hedera*-covering, which was similar to that reported by Bolton et al. (2014)). This may be because there is relatively little contribution from solar gains during this period and external ambient temperatures are lower, which would increase heat transfer to the environment.

Given that *Hedera* has previously shown itself to be a species resilient to pollution, drought, poor soil conditions (Steubing et al., 1989, Dunnett and Kingsbury, 2008, Sternberg et al., 2010b, McAllister and Marshall, 2017), and is an evergreen, it is therefore proposed that it would, if properly maintained, be well suited to any greening scheme that requires year-round cover. By comparison, the deciduous *Parthenocissus* might be best suited for situations where cover is only required during summer months or would be unhelpful in winter. An example would be on a south facing wall on a building where solar gains during winter, uninhibited by leaves, would be beneficial, as would summer cooling from the shading provided by foliage. *Pileostegia* by comparison is a slower growing alternative, of smaller stature, that provides some of the benefits of *Hedera*, but without the negative associations, and therefore may be considered an addition to the 'toolkit' for smaller greening schemes.

In conclusion, the findings have shown that greening is an effective tool (as part of a multi-approach solution) to many of the problems associated with building climate control. Anecdotally, space heating and air conditioning tend to be more expensive to operate than dehumidifiers, therefore, it may be sensible to utilise the benefits of plants for summer cooling and winter insulation, even if RH is slightly increased at times. Therefore, it is felt that, with appropriate precautions, the historical fears concerning the effect of *Hedera* on structure RH could be overcome.

Chapter Four

Computational modelling of the thermal behaviour of *Hedera* cladding

4.1 Introduction

Plants around buildings can moderate temperature in several ways; primarily, during times of high temperature and solar irradiance (summertime), they deliver passive cooling via two processes: evapotranspiration and shading (Cameron et al., 2014). This has been shown many times in situations where double skin façades over windows (bioshaders) and plant layers adjacent to walls have produced measurable reductions in building envelope temperatures (Cameron et al., 2014, Ip et al., 2010, Pérez et al., 2011, Perini et al., 2011). During periods of reduced temperature and solar irradiance (at night-time and during winter), however, the insulation effect provided by the plant-layer appears to marginally exceed its potential shading effect (during daytime in winter), though there may be a delay before the insulation influence at the building envelope is observable inside the building (Cameron et al., 2015, Ottelé and Perini, 2017). Lastly, there are several intermediate situations where neither the cooling nor insulation effects dominate: during spring, autumn, mild winters, and at the northern aspect of a building, when temperatures are approximately 5-12 ^{o}C and solar gains are minimal see Chapter 3 and Bolton et al. (2014).

The thermal impacts of plants on buildings have been successfully modelled in a wide range of programs such as Envi-met (Bruse and Fleer, 1998) and EnergyPlus (Larsen et al., 2014) as discussed in Chapter 1 section 1.5. In order to account for benefits derived from plant-based layers around the building envelope, both Envi-met and EnergyPlus have developed integrated vegetation parameters or modules for structural greening (for example, green roofs). Therefore, the development of vegetation layers in a commercial software package (widely used in industry) may impact many projects, remediating the tendency for plant use to be overlooked due to an inability for designers and architects to model the impacts of vegetation (Mangone and van der Linden, 2014).

Integrated Environmental Solutions; IES (IES VE 2017.1.0.0) software is widely used within industry by major engineering and architectural companies, such as AECOM (IES, 2017), Atkins (Graham, 2005), and ARUP (Maloney, 2016). Its applications have thus far included the modelling of energy consumption within structures such as the Golden One Centre (AECOM (Integrated Environmental Solutions Limited, 2017), Atkins (Graham, 2005)) and the generation of future global weather files based on various emissions and climate change scenarios (ARUP, Argos Analytics and IES's Weathershift™ (Maloney, 2016)).

To date, different building types and façades have been modelled in IES software such as domestic retro-fit options (Simpson et al., 2016), options for shading devices in Abu-Dhabi (Kirimtat et al., 2016), and a study of a timber double-skin facade in a temperate climate (Pomponi and D'Amico, 2017). One of the cooling mechanisms plants can provide is shading and several studies have developed models for trees, these studies simulated the solar path effect and hence the impact of the reduction in buildings' solar gains due to the shade caused by trees using the SunCast aspect of IES software (Hes et al., 2011, Skelhorn et al., 2016). The solar path effect (calculated by the SunCast aspect of IES) is simulated in this study, so that the impact of solar gains with respect to building orientation and shading from plants are included in the simulation.

Relatively few studies, however, have modelled the impact of green walls using IES software (Alabadla, 2013, Laparé, 2013, Tachouali and Taleb, 2015), and no studies were found to compare green wall simulation in IES with other software programmes. One study modelled a green wall as an extra room with a heat ventilation and air conditioning (HVAC) system, to simulate the moisture and air movement within the plant layer (Laparé, 2013), which provided a method to account to the cooling via evapotranspiration from the plant. Additionally, some other studies have modelled green walls; however, one did not explain how the green wall was modelled (Tachouali and Taleb, 2015) and another modelled a living wall system without the plant component (Alabadla, 2013).

Therefore, considering the issues raised above, IES was chosen as it has a user-friendly interface, with a computer-aided design (CAD) style drawing package to create the building (Model-IT), an in-depth thermal simulation modelling package (Apache), and solar path effect simulation (SunCast). Additionally, IES software is used to demonstrate compliance with Part L of the Building Regulations (Lim, 2009, Ministry of Housing Communities & Local Government, 2014). Furthermore, IES software is inexpensive for research and used both academically and commercially, therefore any progress in developing a validated green wall model could be beneficial to commercial developments and increase the use of green walls in designs.

The objective of this study is to develop and validate a model of the cuboids measured in Chapter 3 during summer and early spring, and generate a plant-layer based on the *Hedera*-covering around the cuboids using IES software. Then the simulated results from the model will be matched to the experimental data and the accuracy of the simulated temperature profiles analysed.

4.2 Methodology

The first stage in developing a model (in IES) for validation against the experimental brick cuboids (from Chapter 3) involved generating a reference (bare) model building (Figure 4.1a and Appendix A), based on the dimensions and construction materials of the brick cuboids (Figure 4.1b).

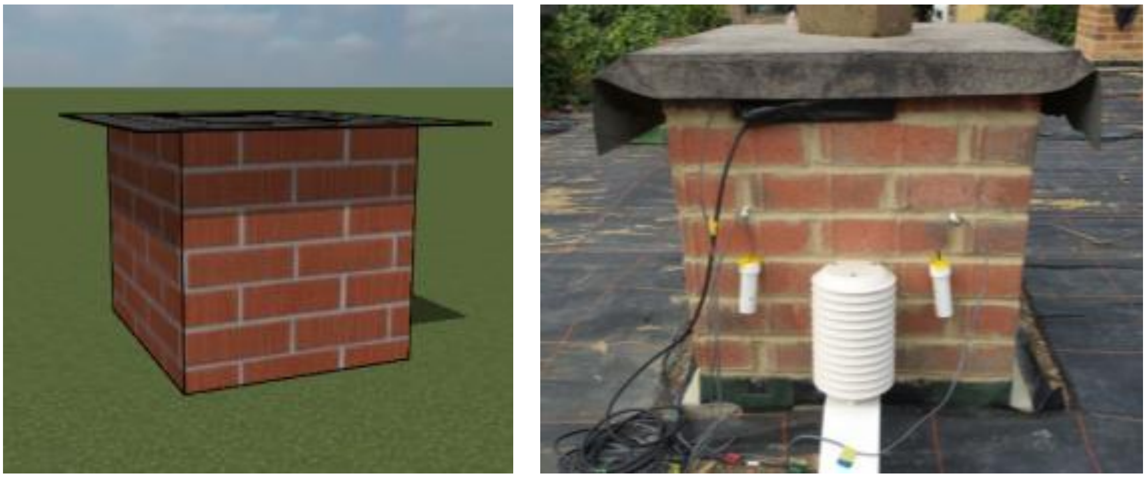

Figure 4.1 L-R: Model cuboid designed in IES (a) and experimental bare cuboid (b); photograph by Faye Thomsit-Ireland

The boundary conditions (inputs) for the model were developed based on the materials used and location of the experimental brick cuboids, which are explained in sections 4.2.1-4.2.4. The modelled cuboid was oriented to 105^{o} of north; based on the aerial photograph of the experimental brick cuboids Figure 2.2 Chapter 2 section 2.6.

4.2.1 Construction materials

The U-value of each construction element (for example, the floor) was calculated in IES software according to methods specified by ISO 13370:2007 (ISO, 2007). The U-values were calculated using properties (such as thickness and thermal conductivity) of the materials within each layer of the construction element along with values for the thermal resistance of the internal (R_{si}) and external surface (R_{se}) air films. Typical values for the surface resistance of high emissivity materials given in ISO 6946: 2007 are used in IES software and displayed in Table 4.1:

Table 4.1 Values for the thermal resistances of internal and external surfaces depending on direction of heat flow

Surface resistance	Direction of heat flow		
(m^2KW^{-2})	Upwards (e.g. through the roof)	Horizontal (e.g. walls)	Downwards (e.g. through the floor to the ground)
R_{si}	0.1	0.13	0.17
R_{se}	0.04	0.04	0.04

The U-value of a construction element e.g. the floor is calculated as per equation [4.1].

$$Thermal\ transmittance\ (U - value)\ of\ a\ construction\ element = \frac{1}{\left(\begin{array}{c} R_{si} + R_{se} + \\ \sum Thermal\ resistances\ (R - values)\ for\ each\ material\ layer\ within\ the\ construction \end{array}\right)} \quad [4.1]$$

The U-values of the construction elements were based on the experimental brick cuboid constructions described in Chapter 2 section 2.6.1 and are presented in Table 4.2. The dimensions of the cuboids were rounded to 0.1 m (Table 4.3). The details of the construction materials and their associated properties, including which parameters were based on the IES software materials database and which were derived or approximated is in Appendix B.

Table 4.2 Construction materials (listed from exterior to interior) and associated U-values used for the modelled buildings in IES software

Construction element	Construction and materials (from exterior to interior)	U value ($Wm^{-2}K^{-1}$) of the construction calculated in IES
Floor	10 mm Stabilising cement 0.3 mm PVC damp-proof membrane 34 mm Aerated concrete slab 0.3 mm PVC damp-proof membrane 18 mm Cavity 2.6 mm Foil covered insulation 18 mm Cavity 18 mm Heavy weight plywood	**1.03**
Wall	103 mm brick	**3.42**
Ceiling/Roof	1.3 mm Bitumen felt 11 mm Weatherboard (Oriented strand board (OSB)) 18 mm Cavity 2.6 mm Foil covered insulation	**2.49**

Table 4.3 Comparison of the experimental and modelled building dimensions

	Internal dimensions of the experimental brick cuboids	Dimensions modelled in IES software
Height (m)	0.500 ± 0.009	0.50
Width (m) (E-W)	0.323 ± 0.006	0.30
Length (m) (N-S)	0.422 ± 0.008	0.40
Floor area (m^2)	0.136 ± 0.005	0.12
Volume (m^3)	0.068 ± 0.003	0.06

When modelling the roofing material covering the brickwork and overhanging the edge (OSB and bitumen felt see Chapter 2 section 2.6.1), it was assumed that the primary function (from a modelling perspective) of those materials was that of shade, therefore local shading was used in the model. The local shade (Figure 4.2) was 200 mm wide to cover the width of brick (100 mm) and bitumen felt overhang (100 mm). This resulted in the roof being constructed in two parts, the shade (as explained above) and the section (marked 'roof area' on Figure 4.2) enclosing the 'room' below (which was generated with the multi-layered construction materials described in Figure 2.3 Chapter 2 section 2.6.1 and the 'ceiling/roof' construction materials Table 4.2).

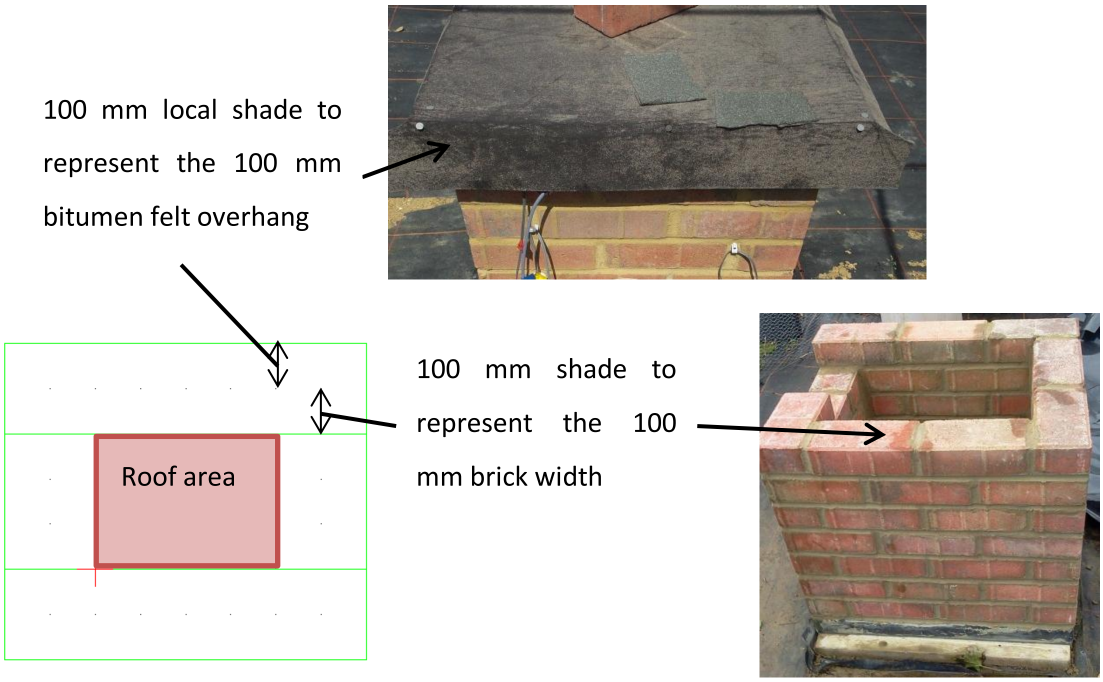

Figure 4.2 Plan view of bare cuboid from IES, showing shading (green outline) around the roof area (pink), with accompanying representation on photographs of the experimental brick cuboids

The winter validation considered the experimental early spring period in March 2015, just after the experimental cuboids had been rebuilt, when the brick cuboids were heated minimally. However, the heating via the oil immersion heaters was considered sufficiently minimal that it was not included in the simulation for either the bare or *Hedera*-covered cuboids (see Chapter 2 sections 2.6.1 and 2.8).

4.2.2 Weather file

A full-year's weather data for Reading was not available within the default data sets. Therefore, a synthetic weather file, extrapolated from the weather data of nearby weather stations was used to develop the data set for Reading. The software used was an interface within Python, mathematically based software. Sections of the synthetic weather file were replaced with measurements made at the University of Reading Meteorological Observatory (UoR MO) during 2015 (the dry bulb temperature, RH, dew point, wind speed and direction at 10 m, and mean sea level pressure were used in place of the synthetic data), assuming minimal impact. Additionally, values measured at the UoR MO for the total global and the diffuse horizontal radiation and estimates of the direct normal radiation (calculated from the total global and the diffuse horizontal radiation) were used in place of the synthetic data, again assuming minimal impact (see summary of assumptions section 4.2.6 for further details). However, the data logger that measured the diffuse solar radiation malfunctioned at the UoR MO from 27/4/15-28/10/15 and no data was collected. Therefore, a numerical method was required to estimate the diffuse solar radiation during that time.

There are several methods to extrapolate the diffuse from the global solar radiation. However, separation or decomposition models can provide estimations based on measurements of the global and extra-terrestrial horizontal solar radiation (see Appendix C for further information). There are many decomposition models available and each has been tailored to the region in which they were calibrated. The Erbs model has been verified as a suitable model for Reading, although it under-estimates diffuse solar radiation when the sky is clear and sunny (Erbs et al. cited by, Burgess, 2015).

The direct (beam) solar radiation measured on the normal plane (perpendicular to the sun rays), direct normal solar radiation, G_n was estimated using equation [4.2] where θ_z is the solar zenith angle, I_G is the global- and I_d is the diffuse solar radiation measured on the horizontal plane ((Lee et al., 2017); see Appendix C for further explanation).

$$G_n = \frac{I_G - I_d}{\cos \theta_z} \qquad \textbf{[4.2]}$$

As cosine varies between +1 and -1, when the zenith angle approaches 90^{o}, the cosine approaches 0, and hence the numerator in equation [4.2] approaches infinity, therefore purely mathematically a method for curtailing that tendency was required. Additionally, pyranometers are also frequently specified to a zenith angle of 80^{o} with an error of around 6% or ± 10 Wm^{-2} per 1,000 Wm^{-2}, above that angle the errors increase, therefore when estimating the direct normal radiation only values of zenith angle less than 80^{o} were considered (Burgess, 2015, Zonen, 2018).

For further information about calculating the diffuse component from the global horizontal solar radiation see Appendix C.

The result of replacing the data in the synthetic Reading weather file, with appropriate values from the data sourced from the UoR MO as described above, produced the weather file 'Reading2015' which was used in the simulation of the model brick cuboids.

4.2.3 Additional inputs

4.2.3.1 Temperature of the ground and air surrounding the cuboids

Within the Apache simulation module of the IES software, the external walls and roof were defined as 'in contact' with the external air temperature and the 'ground' floor of the building was set to be 'in contact' with a constant 13 ^{o}C; the recommended ground temperature in the UK (IES, 2014).

4.2.3.2 Infiltration rate

The air infiltration was measured in 14 brick cuboids using a decay method with CO_2 as a tracer gas (see Appendix D for full explanation of method employed); the mean number of air changes per hour (ACH) measured in the cuboids was 3.6 ± 0.9 ACH, which was used as the infiltration rate in the simulation. A natural logarithmic transformation of the decay curves for three of the cuboids are given in Figure 4.3.

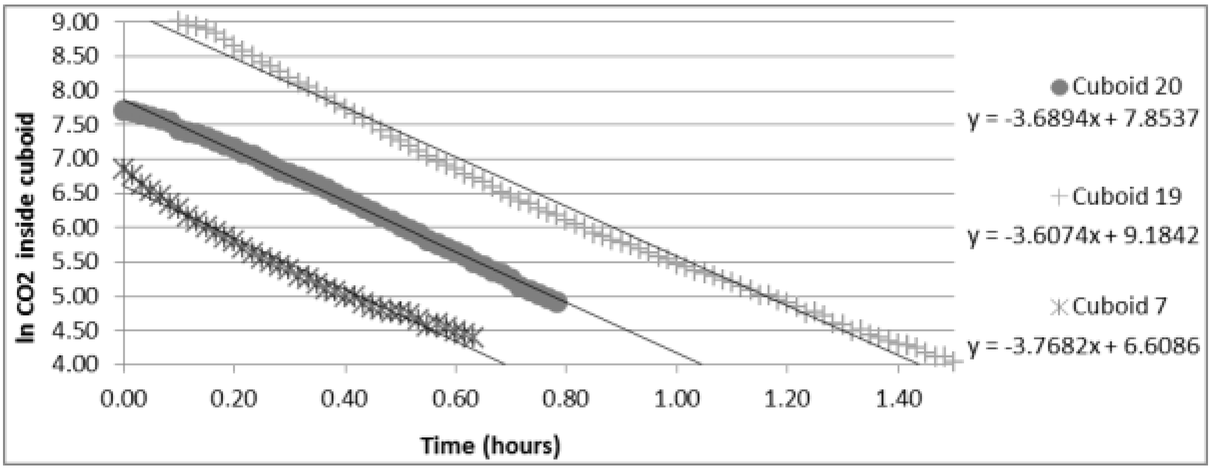

Figure 4.3 Natural log. CO_2 concentration decay curves inside the brick cuboids versus time in hours with trend lines

4.2.3.3 Temperature of the infiltrated air

Within the IES manual on ApacheView, it was suggested that where infiltrated air was warmed by the buildings, an offset could be added to the external air temperature to account for the warming effect (IES, 2014). Therefore, the temperature of the infiltrated air for the external walls of the modelled bare brick cuboids in IES was set to the external air temperature plus 2.6 ^{o}C to account for the average increase due to warming (by the bricks radiating and convecting heat). This value was derived from measurements of the mean difference between the external air temperature measured next to the bare brick cuboids and the ambient air temperature in summer. This offset was not added to the modelled plant-covered buildings as the bricks did not heat the infiltrated air. This is because the brick temperature was not elevated due to the shade caused by the surrounding plants. Additionally, the offset was not added during the early spring simulation as the bricks did not warm the air around them.

4.2.4 Plant-based layer

The second stage of the study involved developing a plant layer for the model using the IES software construction material database; this was done to mimic the *Hedera*-covered cuboids (Figure 4.4a and b). The construction materials database in the IES software requires inputs for parameters including thermal conductivity, specific heat capacity (SHC), and density. Values for these parameters for *Hedera*, *Parthenocissus* or *Pileostegia* had not been measured directly in literature, nor were they calculated experimentally during this project. A study conducted in a controlled environment reported the thermal conductivity (as calculated from surface temperature measurements) of direct greening with *Hedera* (200 mm thick) varied during warm (summer) and cold (winter) temperatures (Ottelé and Perini, 2017).

Figure 4.4 L-R: Model *Hedera*-covered cuboid designed in IES (a) and experimental *Hedera*-covered cuboid (b)

The study gave the results as thermal resistances (R-values), and to calculate the thermal conductivity from those values equation [4.3] was used:

$$Thermal\ conductivity = \frac{Thickness}{Thermal\ resistance} \qquad [\ 4.3\ ]$$

The thickness of the *Hedera*-covering was 200 mm, therefore the thermal conductivity of the *Hedera*-covering over a wall (rather than for example, the thermal conductivity of a *Hedera* leaf) was

0.3 and 1.1 $Wm^{-1}K^{-1}$ during warm and cold temperatures respectively (equations [4.4], [4.5] (Ottelé and Perini, 2017)).

$$Summer\ thermal\ conductivity = \frac{0.2}{0.66} = 0.3\ W/mK \quad [\ 4.4\ ]$$

$$Winter\ thermal\ conductivity = \frac{0.2}{0.18} = 1.1\ W/mK \quad [\ 4.5\ ]$$

The density of *Hedera* from a range of conditions, such as growing over a fence and up a wall, with large woody stems or mainly vegetative leafy growth, was measured as 48-164 kgm^{-3}.

While there appear to be relatively few measurements of the specific heat capacity (SHC) of plant leaves in the literature, the SHC measured at 20 ^{o}C ranged from 1,255-4,000 $Jkg^{-1}K^{-1}$ (Hedlund and Johansson, 2000, Jayalakshmy and Philip, 2010, Jones, 1992). Jayalakshmy and Philip (2010) measured SHC for the fresh leaves of several plant species which were found to be closer to the range for timber (Table 4.4).

Table 4.4 Thermal conductivity of fresh leaves measured at 20 ^{o}C

Species	SHC ($Jkg^{-1}K^{-1}$)	References
Mangifera indica	2263 ± 94	(Jayalakshmy and Philip, 2010)
Cinnamomum verum	2267 ± 65	(Jayalakshmy and Philip, 2010)
Tectona grandis	2232 ± 52	(Jayalakshmy and Philip, 2010)
Cocos nucifera	1287 ± 30	(Jayalakshmy and Philip, 2010)
Myristica fragrans	1255 ± 29	(Jayalakshmy and Philip, 2010)
Artocarpus hirsutus	1637 ± 38	(Jayalakshmy and Philip, 2010)
Timber, (seasoned oak)	2400	(Jones, 1992)
Timber, Pitchpine and Red beech	1300	(The Engineering Tool Box, 2003)

As *Hedera* plants are a mixture of leaves and woody stems, the maximum and minimum values for the SHC of leaves measured by Jayalakshmy and Philip (2010) were used to generate two modelled plant layers ('*Hedera* max' and '*Hedera* min'; Table 4.5).

Table 4.5 Thermal and physical parameters of the *Hedera* layer

	SHC ($Jkg^{-1}K^{-1}$)	Density (kgm^{-3})	Thermal conductivity ($Wm^{-1}K^{-1}$)
***Hedera* max**	2267	164	0.3
***Hedera* min**	1255	48	1.1

The plant layer with higher U-values and hence lower insulation properties '*Hedera* min', used values for the highest thermal conductivity (as that means heat is transferred more quickly though the leaf) and the lowest values for density and SHC, as a less dense substance will allow quicker heat transfer and a lower SHC holds less heat for latent heat transfer and less heat is required to change the temperature of the substance, the reverse was true for '*Hedera* max'.

The mean depth of plant cover measured around each side of the experimental brick cuboids in July 2016 was 250 mm (Table 4.6 and Chapter 2 section 2.5.4). There were no foliage depth measurements made during the experiments and as the plants had been disturbed (pulled away from the buildings and interwoven chicken wire removed from their stems) during the building mortaring in spring 2014 and 2015, therefore a depth of 50 mm was removed from the foliage depths measured in 2016 to account for the additional year's growth (which concurs with the photographs taken during the summer 2015 experiment). Therefore, the foliage depth used for the modelled building simulation was 200 mm.

Table 4.6 Mean foliage depth measured in July 2016

Cuboid number	Treatment	Mean foliage depth (m)
18	*Hedera*	0.24
7	*Hedera*	0.17
15	*Hedera*	0.35
11	*Parthenocissus*	0.21
8	*Parthenocissus*	0.21
14	*Parthenocissus*	0.17
6	*Pileostegia*	0.29
19	*Pileostegia*	0.30
16	*Pileostegia*	0.30

Once the plant layers were developed (Table 4.5), they were added to the modelled building construction (Table 4.7), a simulation was run to correspond with the time of the summer experimental period 2015 in Chapter 3 (26th June-18th July 2015).

Table 4.7 Elements for each part of the construction, the layers are labelled in order from exterior to interior

Wall Construction	Material and thickness	U-value for complete wall construction ($Wm^{-2}K^{-1}$)
'*Hedera* max'	200 mm *Hedera* layer max 103 mm Brickwork	**1.04**
'*Hedera* min'	200 mm *Hedera* layer min 103 mm Brickwork	**2.11**

Once the parameters were found for a plant layer that accurately represented the trends for the internal temperature of the modelled building compared to the experimental cuboids in summer, those values were used to validate the model in early spring.

4.2.5 Statistical analysis

4.2.5.1 Measuring the difference between the simulated and the experimentally measured values: Standard deviation

To generate the mean standard deviation between the two data sets, the standard deviation was calculated for paired (between the experimental and simulated) results for each time period (for example, 01:30 26th June). Then the mean standard deviation was calculated, to find out how the experimental and modelled data varied throughout the experimental period 26th June-18th July. A similar technique was used to calculate the standard deviation for the experimental data set, for each time period the standard deviation was calculated between the measured results of the experimental cuboids with the relevant treatment. Then the standard deviations were averaged over the full experimental period 26th June-18th July 2015 or in March 2015 for the early spring results.

4.2.5.2 Absolute percentage difference

The percentage difference was also calculated for paired (between the experimental and simulated) results for each time period. However, as some of the simulated data (as shown in the results sections 4.3.2 and 4.3.3 Figure 4.14 and 4.18), both over- and under-estimated the internal south wall surface temperature, once the percentage difference was calculated the value was taken as an absolute (i.e. without the sign) equation [4.6]. The result of using the absolute was that when the values were averaged, the total average difference between the simulated and experimental values would be calculated.

$$absolute\ value\left(\left(\frac{experimental\ value - model\ value}{experimental\ value}\right) \times 100\right) \qquad [\ 4.6\ ]$$

4.2.6 Summary of assumptions and relevant facts

4.2.6.1 Solar inputs into the Reading weather file converted from the UoR MO data

- The units for solar radiation were Wm^{-2} in the UoR MO data, which were collected every hour (therefore not cumulative over the day) and were therefore equivalent to the Whm^{-2} units given in the synthetic weather data file.
- Where a negative value (due to a malfunction in the pyranometer) for total global radiation was recorded in the UoR MO data, this was replaced with a zero value.
- Where the UoR MO was unable to measure diffuse radiation due to logger malfunction (from 27th April-27th October 2015 e.g. during the summer experimental period) the diffuse radiation was estimated from the global horizontal solar radiation, using the Erbs model

which has been previously validated for Reading see Appendix C for further information (Erbs et al. cited by, Burgess, 2015).

- The direct normal radiation was calculated using equation [4.7] see Appendix C, trimming values for the zenith angle greater than 80^o:

$$\frac{Total\ global\ radiation - Diffuse\ horizontal\ radiation}{\cos zenith\ angle} = Direct\ normal\ radiation \quad [\ 4.7\ ]$$

4.2.6.2 Using local shade as part of the flat roof construction

- There would be minimal heat transfer through the roof materials overlapping the brick, compared to the heating from solar gains on the S, E and W walls (though this assumption was neither tested nor confirmed).

4.2.6.3 Construction materials

- The values such as those for SHC, thermal conductivity, density, reflectance given in the IES construction materials database for weatherboard, outer leaf bricks, plywood, aerated concrete slab were representative of the same values in the materials used in the building construction (Figures 2.3 and 2.4 in Chapter 2 section 2.6.1).
- While the wooden batons maintaining the cavity gaps in both the suspended floor and ceiling in the modelled building would act as thermal bridges to the insulation provided by the cavity, a bridged cavity material was generated to simulate the effect in the IES software, however, the difference was negligible (± 0.01 ^{o}C) when the simulation was conducted (data not shown) so that effect was ignored.
- Thermal bridging between construction elements (for example, the ceiling to the walls), is not considered when modelling in IES software; however, this was not considered an issue for this model as the U-values are high compared to more insulated buildings.
- The *Hedera* direct greening used by Ottelé and Perini (2017) to calculate the values for thermal conductivity was representative of the *Hedera* that covered the experimental brick cuboids.
- The *Hedera* plants used to calculate the range of densities for the model were representative of the *Hedera* growth around the experimental brick cuboids.
- The SHC for leaves is the same as the SHC for the whole plant acting as a cladding layer.

4.2.6.4 Time stamps

- The UoR MO data is assumed to be in coordinated universal time format (UTC) as it is marked with a UTC stamp and does not have any missed hours at the time of daylight saving in the UK in March when the clocks are moved forward.

- The IES software has an option to account for daylight saving (which was accepted between April and October).
- The experimental data was operating on British summer time (BST) as the logger time format was set by the clock on the computer, whenever the loggers were checked, which would have been running on BST.
- While there are various internal temperatures that could be compared, neither the options in the IES software, nor the temperatures measured experimentally exactly match. Therefore, the surface temperature option was used in the IES software along with the experimental data solely from the thermistors which were the closest to the wall surface and therefore likely produce the closest match to measuring the wall temperature.
- During the early spring comparison (March 2015) the experimental data logger was assumed to be running in UTC as although British summer time (BST) started on 29th March at 01:00, a computer was not attached to the logger until the 30th March 2015 to download the data file, therefore the 'logger clock' would not have been updated.

4.3 Results

4.3.1 Bare cuboid simulated during summer

The results of simulated and experimental internal temperature profiles are presented in Figure 4.5 to provide an overview of the modelling accuracy during the experimental period. There was, however, a logger malfunction between 18:30 6th July 2015 and 17:30 7th July 2015, where no data was recorded, therefore this time is marked on all relevant graphs to identify the break. A regression between the experimental and simulated internal temperature was conducted (Figure 4.6). This showed a strong correlation between the data sets (R^2 = 0.945). However, despite the consistent trend, the simulated results constantly under-estimated the internal south wall temperature compared to the experimental data (Figure 4.5), with a mean standard deviation for the experimental period of ± 2.03 ^{o}C. The mean standard deviation between the simulated and experimental data sets for the bare cuboids was greater than the mean standard deviation of the experimental bare cuboids over the experimental period which was ± 0.5 ^{o}C. The deviation from the experimental data would have been due to the input conditions at the boundary (of the model) where values were estimated, or default values were used where actual measured data could not be sourced. Additionally, for the experimental period, the mean percentage difference was 12.7% between the experimental and simulated internal south wall surface temperatures (Figure 4.5). While the mean percentage difference was statistically high, it was due to a constant under-estimation of the experimental data by the simulated results.

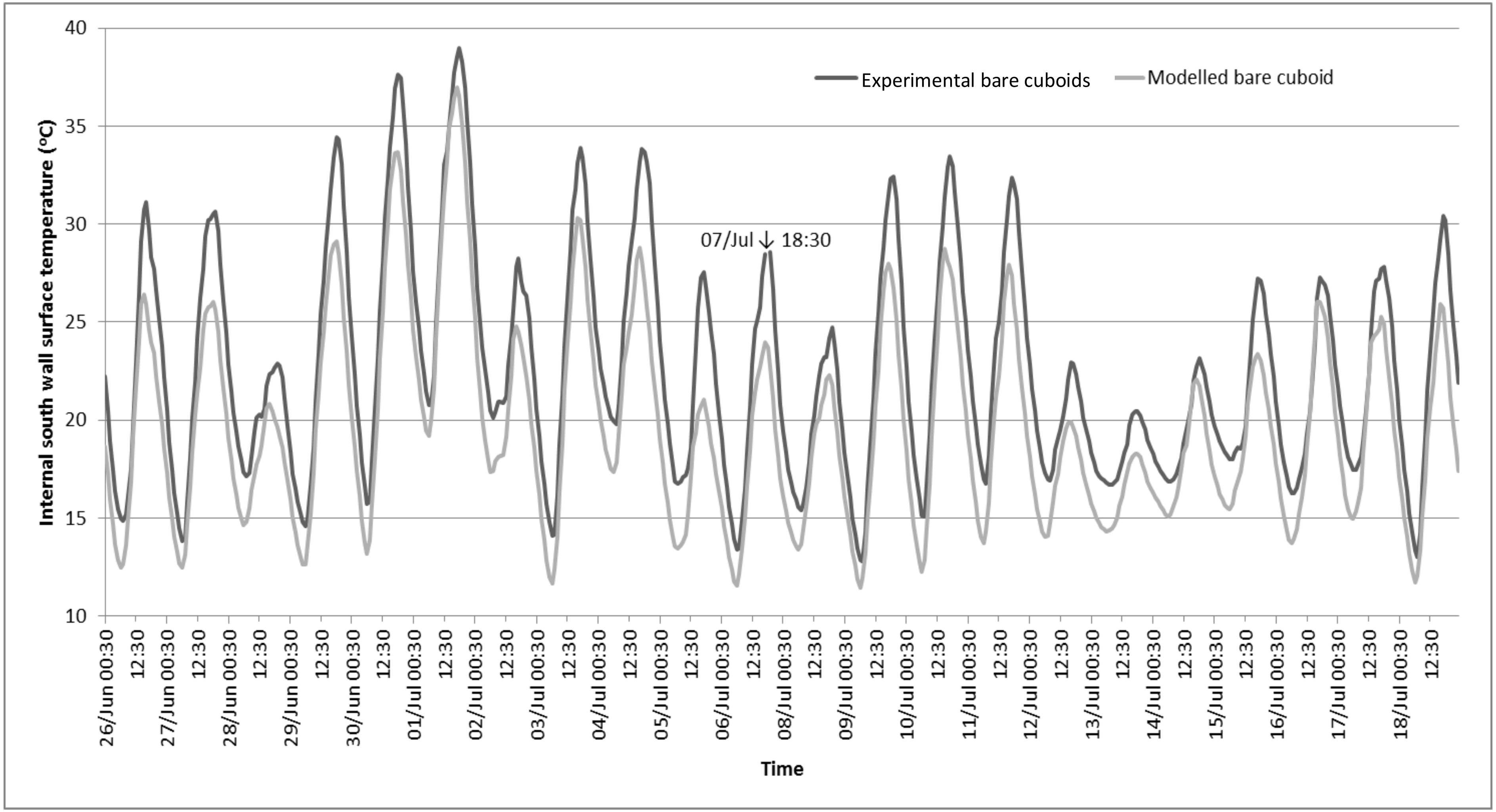

Figure 4.5 Full time series during summer (26th June-18th July 2015), showing similarity in the internal south wall surface temperature profile between the experimental and simulated bare brick cuboids versus time, no phase shift (full 24 hour gap in data due to logger failure from 18:30 6th July to 17:30 7th July not shown)

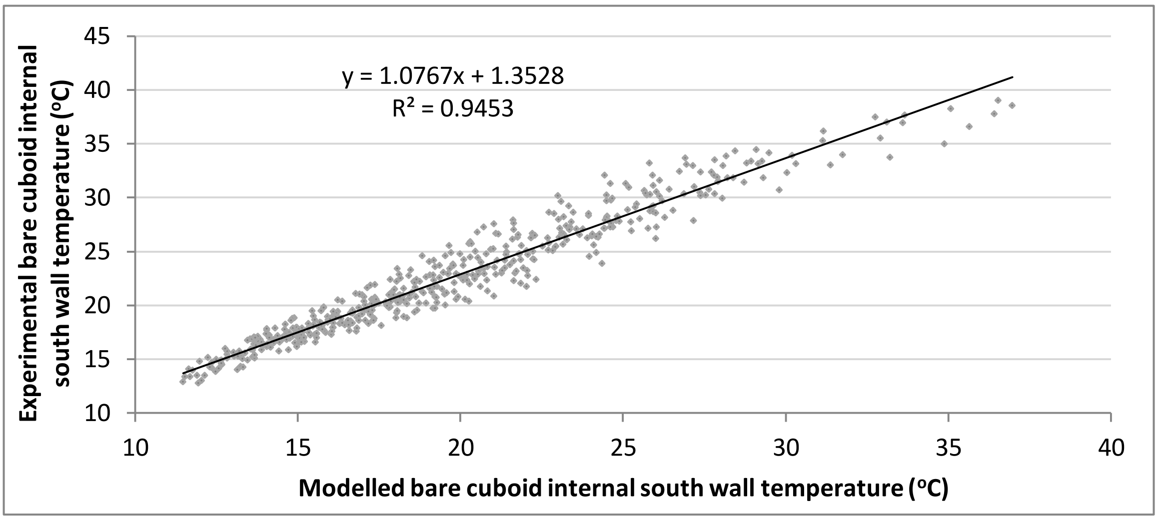

Figure 4.6 Regression between the internal south wall surface temperatures of the experimental and simulated bare cuboids with associated trend line and coefficient of determination

One area of deviation between the two data sets was that the maximum and minimum temperatures occurred an hour earlier in the modelled buildings compared to the experimental cuboids (Figure 4.7).

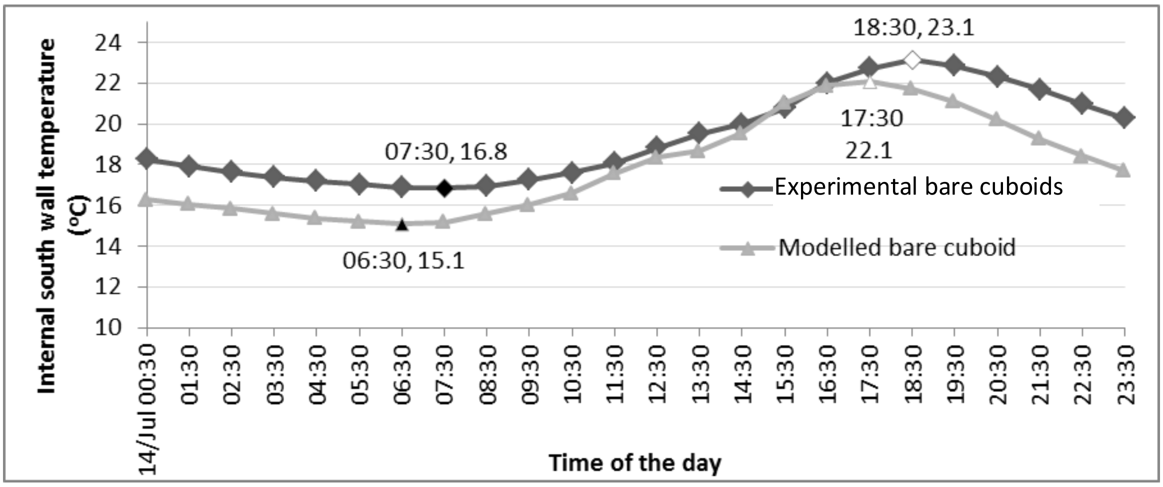

Figure 4.7 Time series for one day (14th July 2015), showing the phase shift between maximum and minimum internal south wall surface temperatures occurring in the experimental and simulated bare brick cuboids. Data labels identify time and value for minimum (black fill) and maximum (white fill) temperature

This difference (as shown in Figure 4.7) indicated that there was an hour phase shift (the modelled and experimental data were asynchronous, even though the loggers were synchronised at every data retrieval), which occurred despite activating daylight saving under the weather location options in the IES software. This implied that the effect was unlikely to be due to a difference in time stamps between the simulated and experimental data (see section 4.6.2.4), possible reasons are discussed in section 4.4.3. Therefore the simulated data was manually realigned with the experimental data, which corrected the phase shift (Figure 4.8).

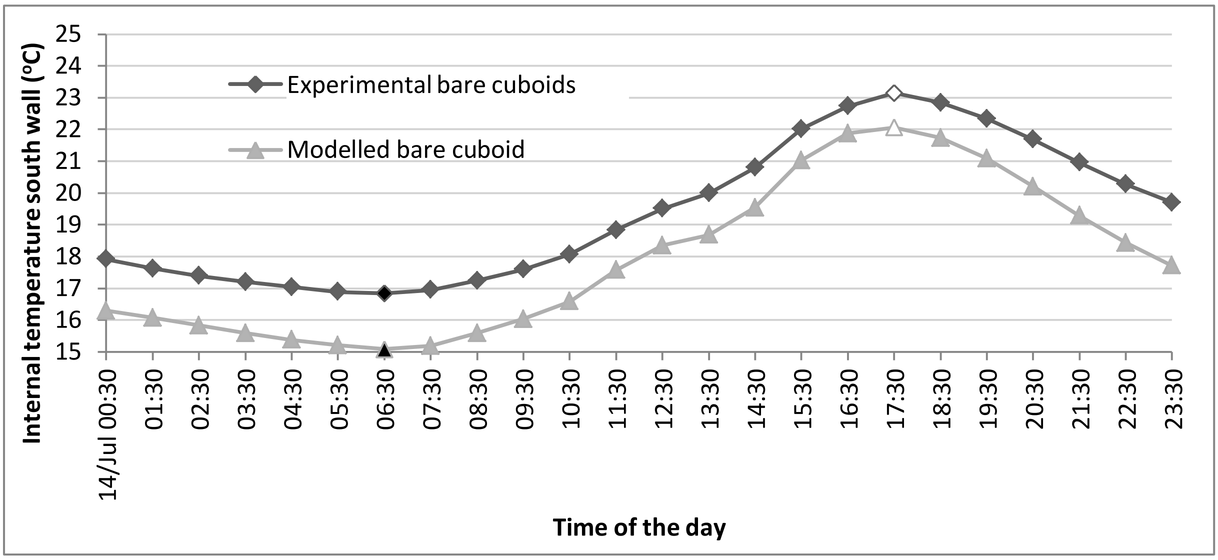

Figure 4.8 Time series for one day (14th July 2015), showing strong correlation between the experimental and simulated internal south wall surface temperature profile versus time of the bare brick cuboids, minimum (black fill) and maximum (white fill) temperature

Both the mean standard deviation and mean percentage difference over the experimental period remained unchanged after the phase shift correction was applied; however, the correlation between the data sets marginally improved to R^2 = 0.961 (Figure 4.9).

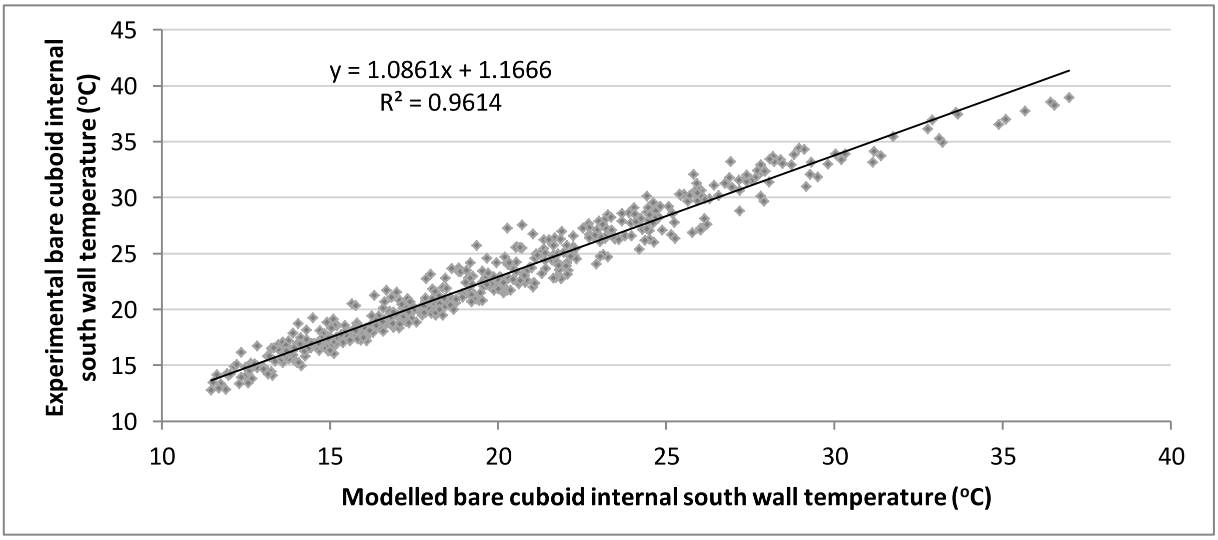

Figure 4.9 Regression between the internal south wall temperatures of the experimental and simulated bare brick cuboids with associated trend line and coefficient of determination

Despite this correction, some days were simulated more accurately than others and the daily mean standard deviation between the two data sets ranged from ± 1.04-2.78 ^{o}C. The day simulated most accurately was 14th July (Figure 4.8) which had a mean daily standard deviation of ± 1.04 ^{o}C and a very strong correlation R^2 = 0.992. There were two types of inaccuracy identified in the simulated results. The first type of inaccuracy related to a failure in simulating the daily experimental temperature profile, for example, during 28th June (Figure 4.10), and led to a reduction in the correlation between the two data sets (R^2 = 0.943).

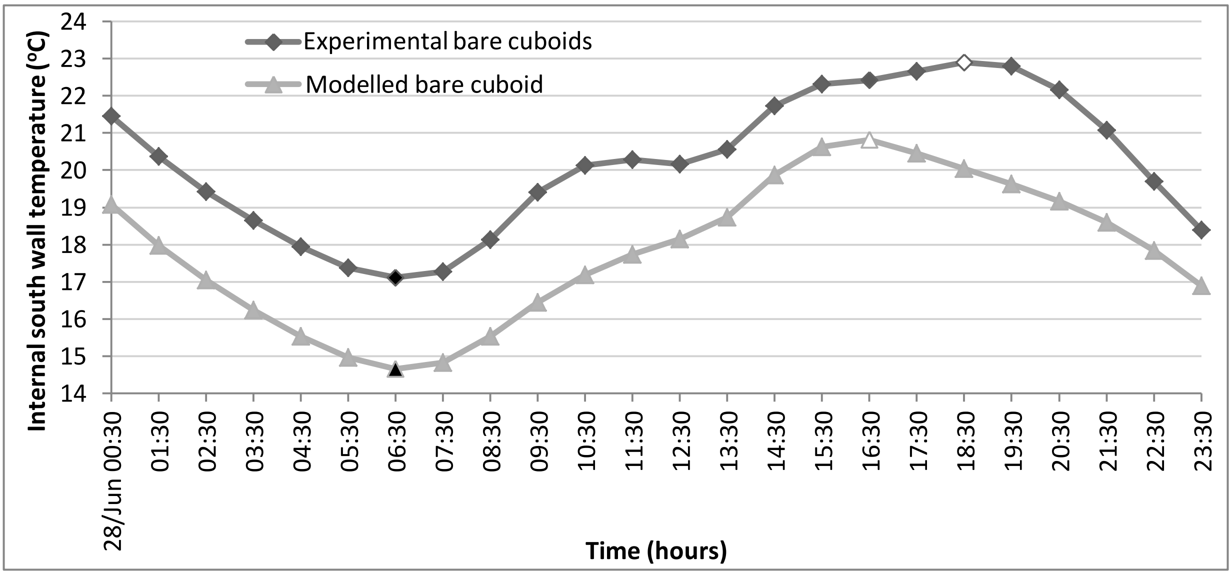

Figure 4.10 Time series for one day (28th June 2015), showing weaker correlation between the internal south wall surface temperature profiles of the experimental and simulated bare brick cuboids versus time, minimum (black fill) and maximum (white fill) temperature

The causes of the differences between the simulated and experimental data were investigated. A notable ‘event’ in the weather data, was that the data collected from 07:00-20:00 indicated an overcast sky (with low < 330 Wm^{-2} global horizontal radiation measurements and less than two hours of recorded sunshine, apart from at 13:00 when the global horizontal radiation increased to 760 Wm^{-2}). However, other less detailed historical weather services (Time and Date AS, 2018), recorded the weather as partially sunny in Reading. Therefore, a difference in the weather used for the simulation (such as due to a logger malfunction or shade over the solar sensor at the UoR MO) and that experienced at the brick cuboids, and the resulting impacts of the thermal mass effect (as heat stored by the brickwork is transferred to the internal environment) may explain the differences in the simulated and experimental data during that time. Nevertheless, the daily mean standard deviation, was ± 1.66 ^{o}C for 28th June (which was mid-range compared to the experimental period) therefore, this form of inaccuracy did not generate the highest standard deviation between the data sets.

The second type of inaccuracy in the simulated results was found on, for example, 11th July (Figure 4.11) and occurred despite strong correlation between the data sets (R^2 = 0.988). While the daily temperature profile was simulated accurately, the simulated results constantly under-estimated the internal temperature, hence there was a difference in the mean daily temperature about which the profile occurred. These inaccurately simulated results were classified as being 'vertical offset', as the simulated data required translating on the y-axis to match experimental data. A constant difference between the two data sets, such as the simulated data under-estimating the experimental data by approximately 4 °C (Figure 4.11) resulted in the highest mean daily standard deviation between the two data sets, which was ± 2.78 °C for 11th July.

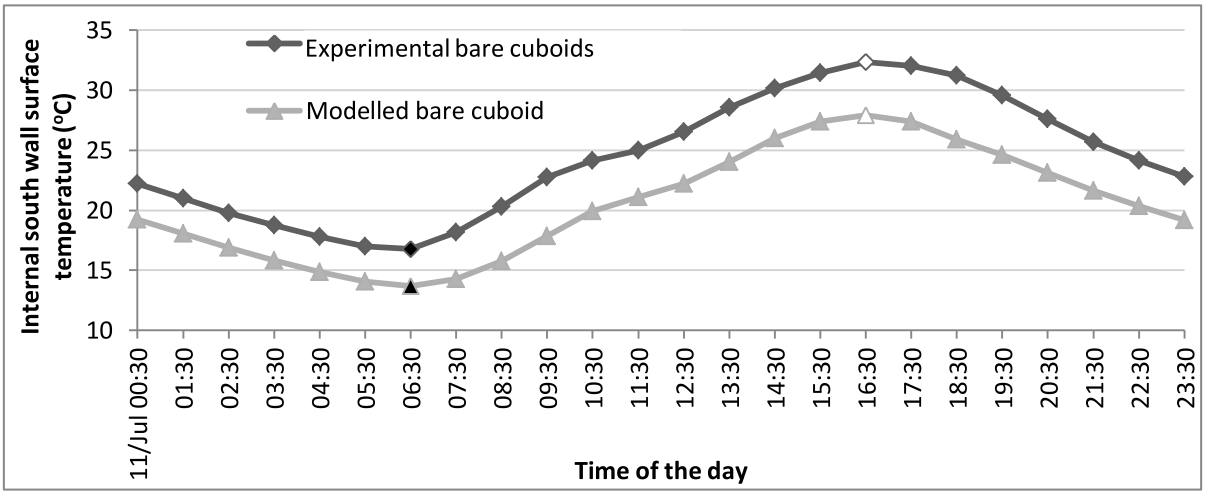

Figure 4.11 Time series for one day (11th July 2015), showing difference in daily internal south wall surface temperature profiles (hence a vertical shift) between the experimental and simulated bare brick cuboids versus time, minimum (black fill) and maximum (white fill) temperature

Additionally, when the mean temperature over the entire experimental period was calculated the means were 22.6 °C and 19.7 °C for the experimental and modelled buildings respectively (Figure 4.4), which indicated that the modelled buildings were on average 2.9 °C cooler. That difference was manually applied to the simulated data (2.9 °C was added to each of the simulated values which shifted the data up the y-axis) to match the experimental data producing Figure 4.12.

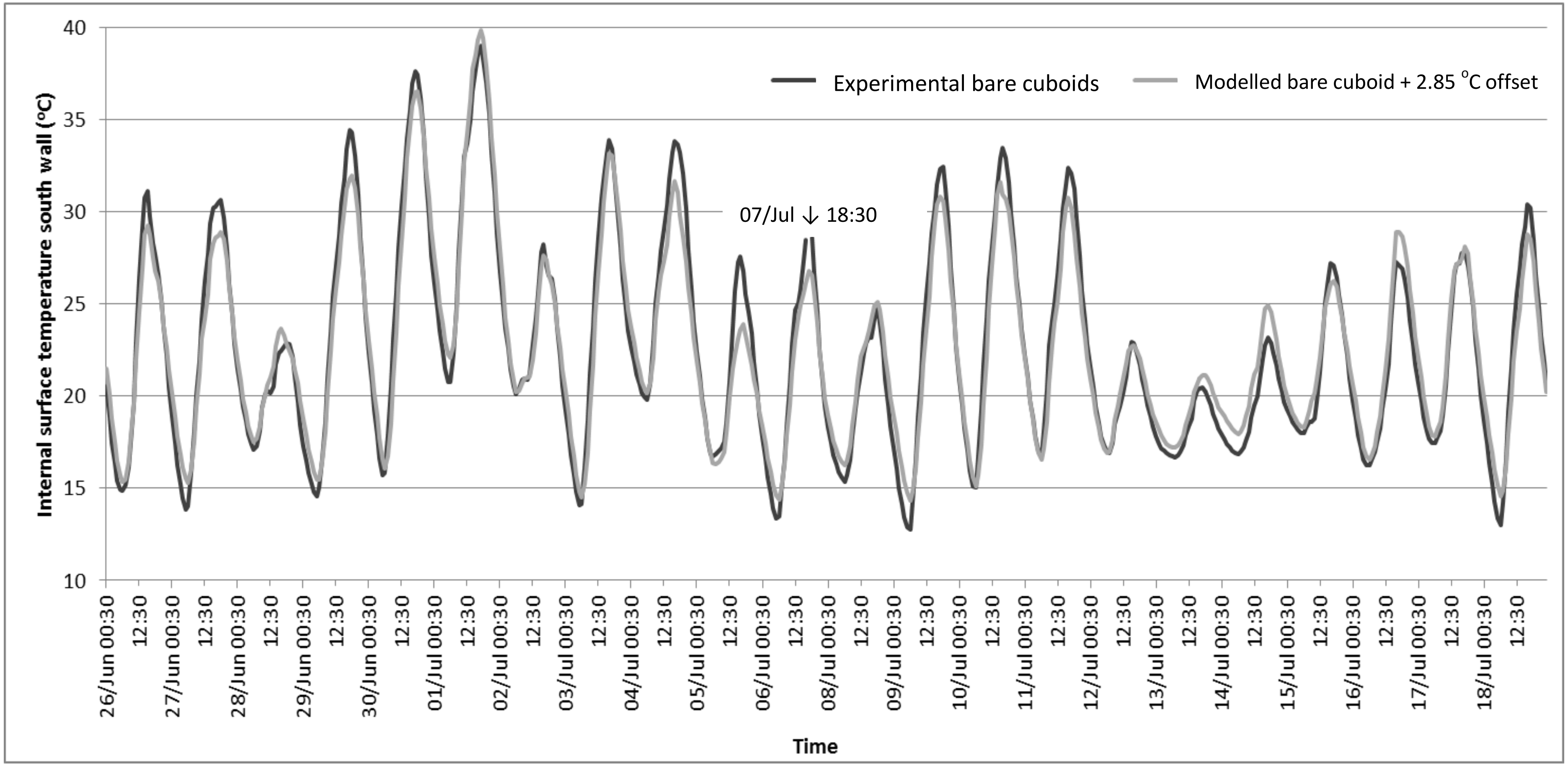

Figure 4.12 Full time series during summer (26th June-18th July 2015), showing variable accuracy in matching between the internal south wall temperature trends of the experimental bare cuboids versus the simulated bare cuboids with 1-hour phase shift and 2.85 °C vertical offset added versus time (full 24 hour gap in data due to logger failure from 18:30 6th July to 17:30 7th July not shown)

After the vertical offset and phase shift were added (Figure 4.12), the temperature profiles for the simulated and the bare modelled buildings matched very accurately (± 0.69 ^{o}C mean standard deviation and 4.4% absolute percentage difference, between the two data sets); however, the correlation was unaffected. There were, however, 64% of days where the peak temperatures were under-estimated and 77% of days where the minimum temperatures were over-estimated, which again implies there was a discrepancy between the boundary conditions used in the simulation and those found in the experiment.

As the under/over-estimation of the simulated data compared to the experimental data did not apply to 100% of the days throughout the experimental period, this implies some form of variable local effect. Localised effects could include air flow around the buildings, interactions with buildings not modelled but present at the experimental site and, for example, the thermal conductivity of the bricks on days of high ambient RH being higher than those of dry bricks.

4.3.2 *Hedera*-covered cuboid simulated during summer

When '*Hedera* max' was modelled, the simulated results under-estimated the internal temperature during 'daytime' and over-estimated the temperature during 'night-time' (Figure 4.13). The under/over-estimation indicated that the layer was too insulating compared to the experimental data for the *Hedera*-covered buildings. Also, the difference between the minimum and maximum daily temperatures of the temperature profile for '*Hedera* max' was between a quarter and half, that of the experimental data. Both of these factors, the difference in the daily maximum and minimum temperatures and the over/under estimation relate to the thermal diffusivity of the '*Hedera* max' layer. The thermal diffusivity is calculated from the specific heat capacity (SHC), thermal conductivity, and density of a material, equation [4.8] (Venkanna, 2010).

$$thermal\ diffusivity = \frac{thermal\ conductivity}{SHC * density} \quad [\ 4.8\ ]$$

As the thermal diffusivity increases, the time difference between changes in the external environment affecting the internal environment decreases; hence there was less temporal lag, resulting in higher maximum and lower minimum temperatures (Venkanna, 2010).

The reduced internal temperature difference observed when '*Hedera* max' was simulated compared to the experimental data indicated that the thermal diffusivity was too low, hence one of, or a combination of, the components of the equation [4.8] were incorrect. For example, the thermal conductivity was too low, or the SHC and the density were too high, all of which were the case for

'*Hedera* max' compared to the '*Hedera* min' layer (Table 4.5), hence the '*Hedera* min' layer was simulated. The '*Hedera* min' layer matched the experimental data for the *Hedera*-covered cuboids much more closely (Figure 4.14), with a strong correlation (R^2 = 0.956), a mean standard deviation of ± 0.46 ^{o}C, and an absolute percentage difference 3.3%. The mean standard deviation between the simulated and the experimental data was much closer to that of, the mean standard deviation of the experimental data for the experimental period, which was ± 0.47 ^{o}C, therefore the '*Hedera* min' layer was selected for simulation during the early spring scenario. There were 73% and 64% of days where the maximum and minimum temperatures respectively were under-estimated.

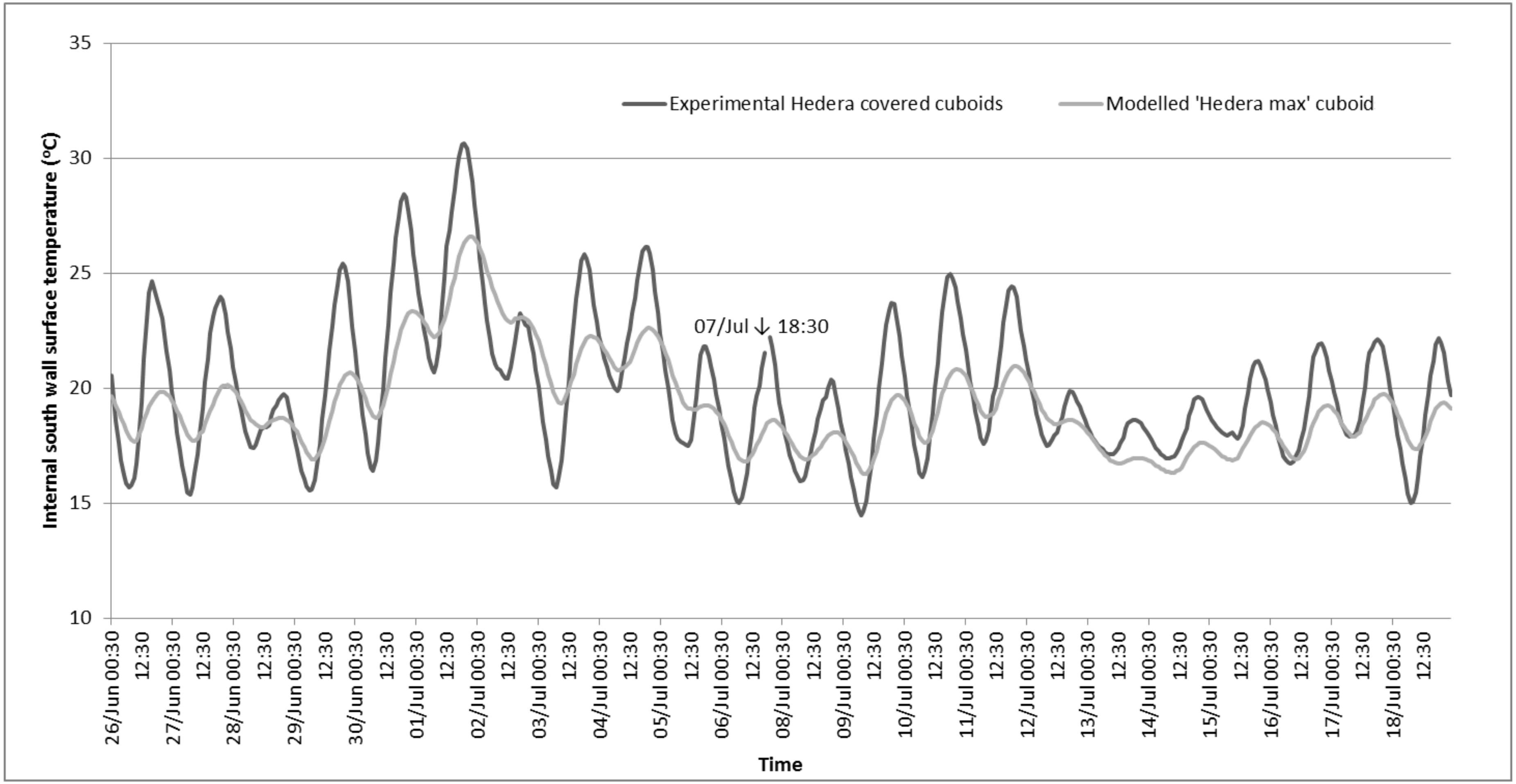

Figure 4.13 Full time series during summer (26th June-18th July 2015) between the internal south wall temperatures of the experimental *Hedera*-covered cuboids and those with the '*Hedera* max' layer simulated (full 24 hour gap in data due to logger failure from 18:30 6th July to 17:30 7th July not shown)

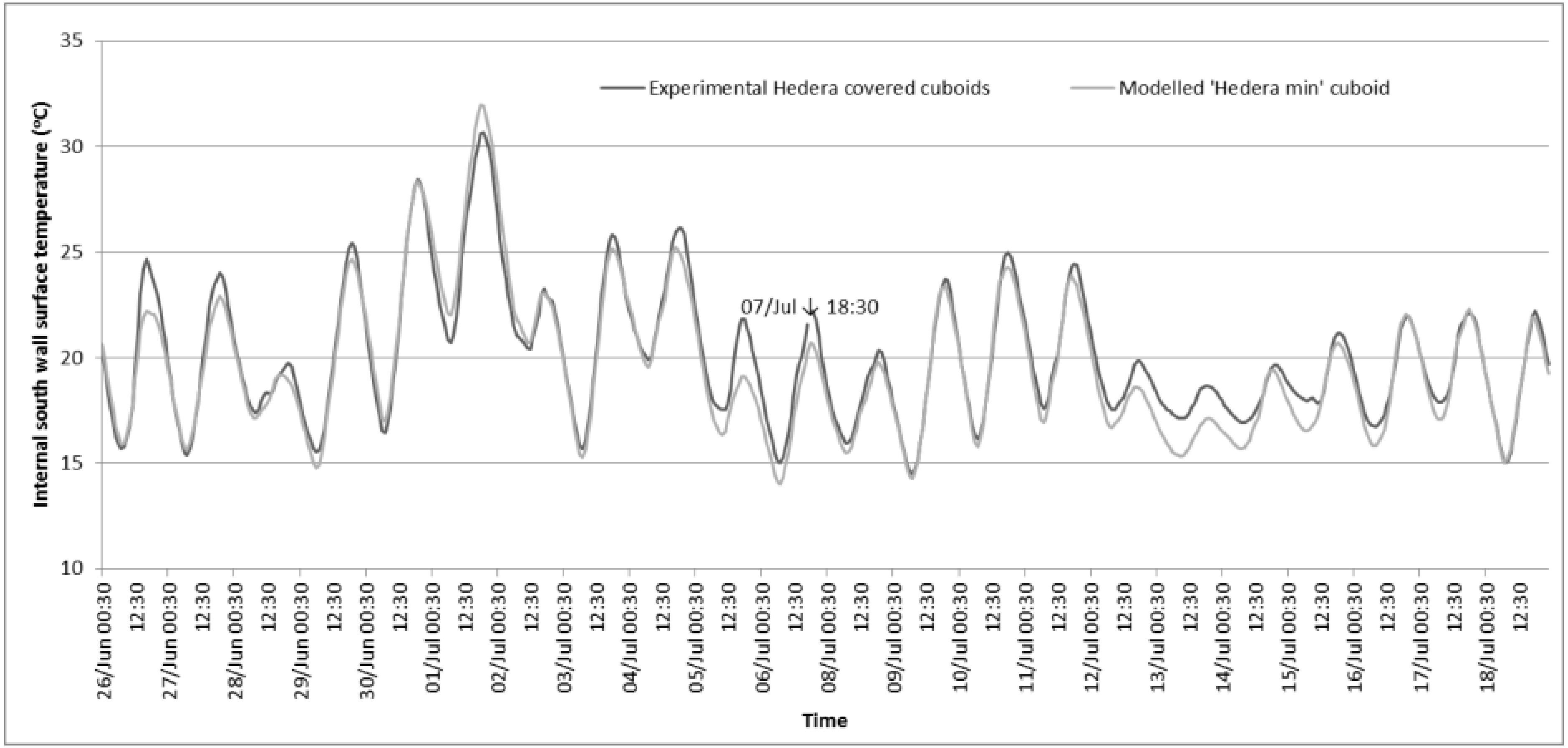

Figure 4.14 Full time series during summer (26th June-18th July 2015) between the internal south wall temperatures of the experimental *Hedera*-covered cuboids and those with the '*Hedera* min' layer simulated (full 24 hour gap in data due to logger failure from 18:30 6th July to 17:30 7th July not shown)

During the experimental period, the daily mean standard deviation between the '*Hedera* min' simulated and the experimental data ranged from ± 0.14-1.03 ^{o}C. Some days were simulated more accurately than others, such as 9th July (Figure 4.15), which had a strong correlation (R^2 = 0.996) and a low daily mean standard deviation ± 0.14 ^{o}C, between the data sets. Notably, the weather on the 9th July represented conditions for high evapotranspiration from the *Hedera* (namely between 09:00 and 17:00, mid-range solar irradiance 570-899 Wm^{-2}, RH 34-46%, and temperature 17-21 ^{o}C).

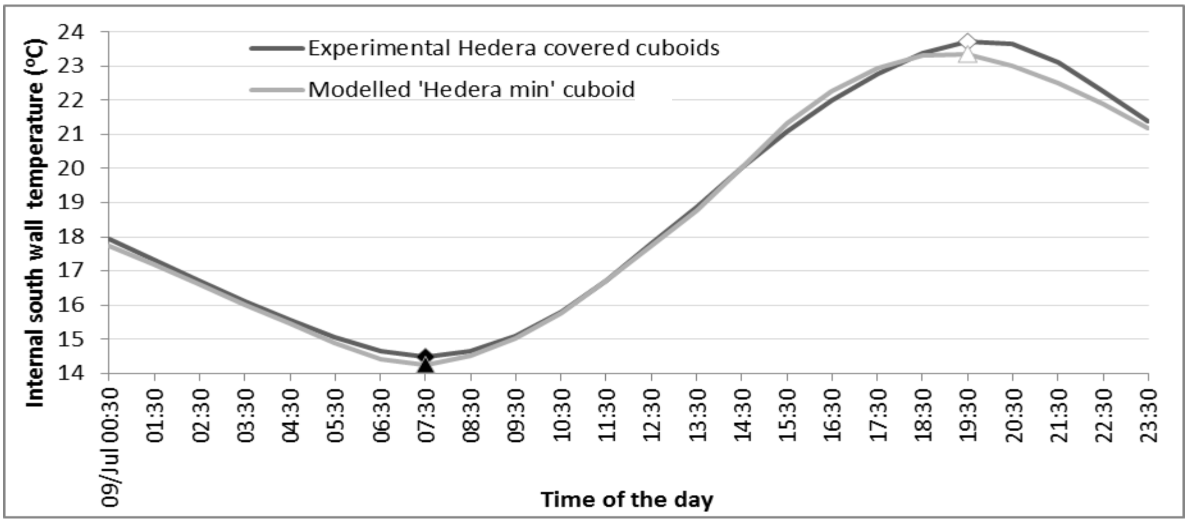

Figure 4.15 Time series for one day (9th July 2015), showing strong correlation between the internal south wall temperature profiles of the experimental *Hedera*-covered cuboids and those with the '*Hedera* min' layer simulated versus time, minimum (black fill) and maximum (white fill) temperature

There were, however, similar forms of inaccuracy in the simulated results of the *Hedera*-covered cuboids to those found in the results of the bare cuboid simulations. Some days such as 28th June (Figure 4.16), showed a weaker correlation (R^2 = 0.911), as the shapes of the daily internal temperature profiles were not fully matched, though the standard deviation between the data sets (± 0.26 ^{o}C) was in the middle of the range for the experimental period.

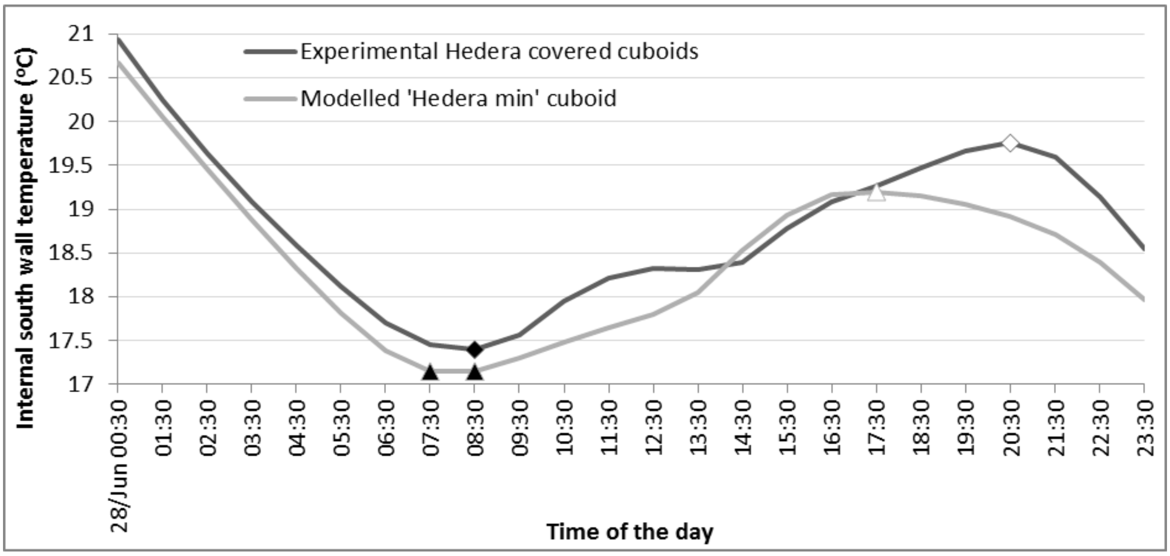

Figure 4.16 Time series for one day (28th June 2015), showing weak correlation between the internal south wall temperature profiles of the experimental *Hedera*-covered cuboids and those with the '*Hedera* min' layer simulated versus time, minimum (black fill) and maximum (white fill) temperature, the minimum temperature for the simulated data plateaued, hence there are two minimums marked.

The shape of the temperature profile for the experimental data of the *Hedera*-covered cuboids was similar to that found in the experimental bare cuboids as detailed in Figure 4.10 (namely an increased temperature difference between the two data sets between 09:30 and 13:30 for the *Hedera*-covered and 08:30 and 12:30 for the bare cuboids). This indicated that the difference in between the experimental (both bare and *Hedera*-covered) and simulated temperatures may have been due to conditions (such as the weather event described in section 4.3.1) that affected all the experimental cuboids. However, there were days such as 13th July, where the simulated data constantly under-estimated the experimental data (by approximately 2 ^{o}C), although a strong correlation (R^2 = 0.978) and daily mean standard deviation ± 1.03 ^{o}C (Figure 4.17) was observed between the two data sets. In this case the weather represented conditions for low evapotranspiration rates by the plants (such as high ambient RH 82-96%, low solar irradiance 60-170 Wm^{-2}). This may explain the difference between the results of the *Hedera*-covered experimental and modelled cuboids, as the experimental cuboids were not cooled further by evapotranspiration on this day.

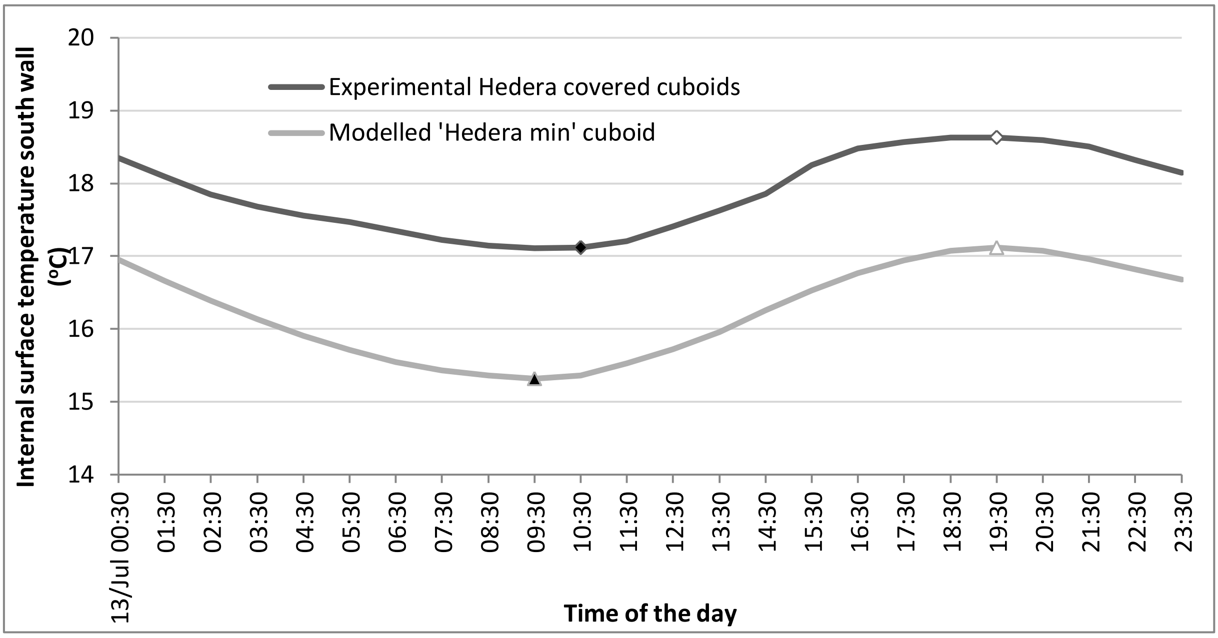

Figure 4.17 Time series for one day (13th July 2015), showing a vertical offset between the internal south wall surface temperature profiles of the experimental *Hedera*-covered cuboids and those with the '*Hedera* min' layer simulated versus time, minimum (black fill) and maximum (white fill) temperature

4.3.3 Bare cuboid simulated during early spring

When the bare modelled building was simulated in early spring and compared to the data from the experimental cuboids, there was no phase shift between the data sets (Figure 4.18, the mean standard deviation was ± 1.78 ^{o}C, and the absolute percentage difference was 26.2%, between the two data sets). The mean standard deviation between the simulated and experimental internal temperatures of the bare cuboids was greater than the mean standard deviation within the experimental internal temperatures for the bare cuboids which was ± 0.51 ^{o}C. Additionally, the simulated data was strongly correlated to the experimental data ($R^2 = 0.924$), though the correlation was weaker than for summer; Figure 4.6. However, the simulated data under-estimated the internal south wall temperature for 65% days, for the other 35% days the simulated results for the daytime internal temperature was either accurately or over-estimated while the 'night-time' temperature was constantly under-estimated.

A vertical offset of 2.45 ^{o}C was manually applied to the simulated data (Figure 4.19, mean standard deviation and absolute percentage difference ± 0.56 and 7.1% respectively); however, the correlation was unaffected. The use of the offset resulted in the simulated internal peak temperature being over-estimated for 39% of days, and under estimated for 26% of days; additionally the minimum temperature was over estimated for 13% of days and under estimated for 52% of days.

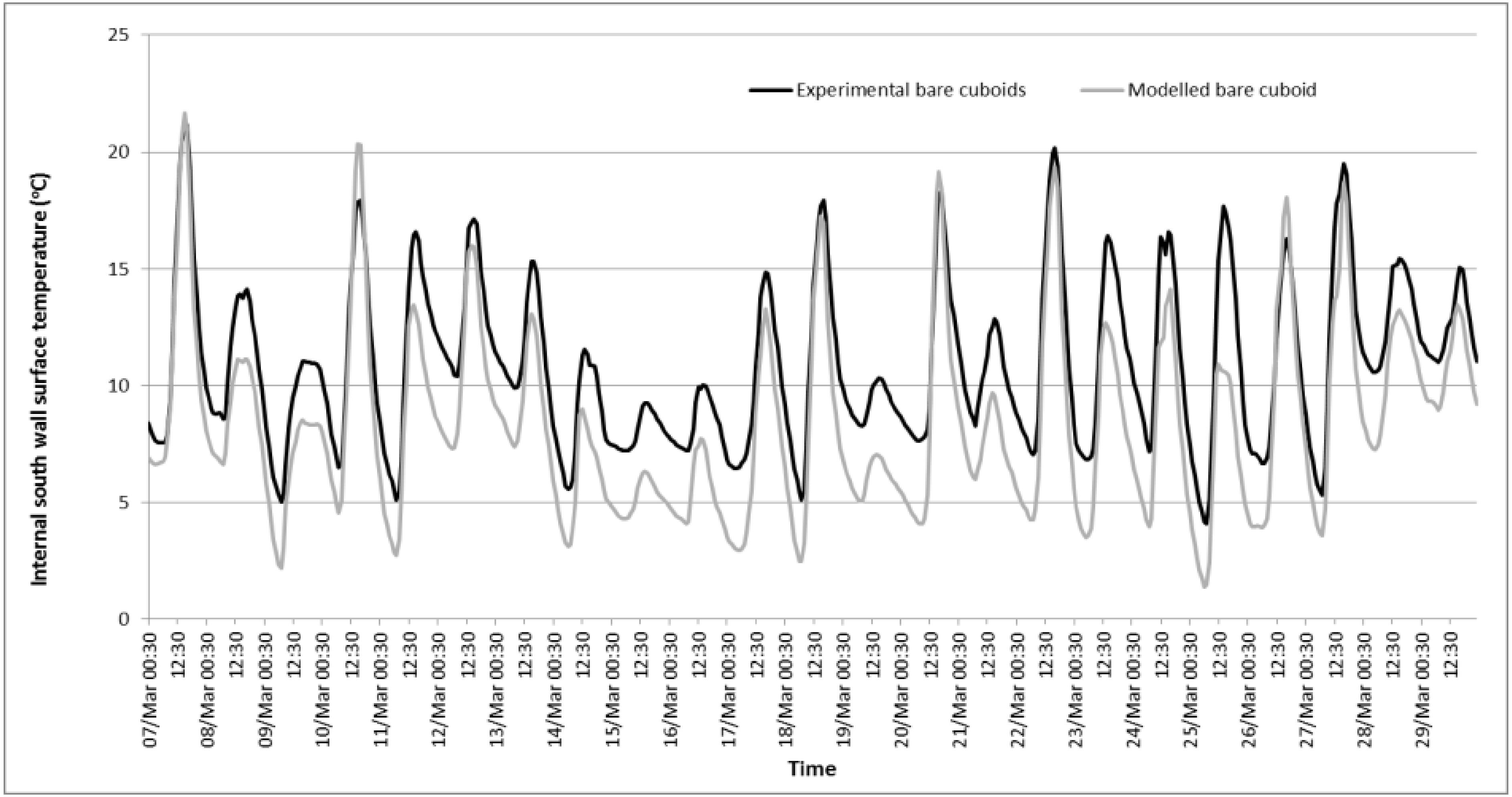

Figure 4.18 Full time series during early spring (7th-29th March 2015) showing variable accuracy in simulating the experimental internal wall surface temperature trends of the bare brick cuboids versus time

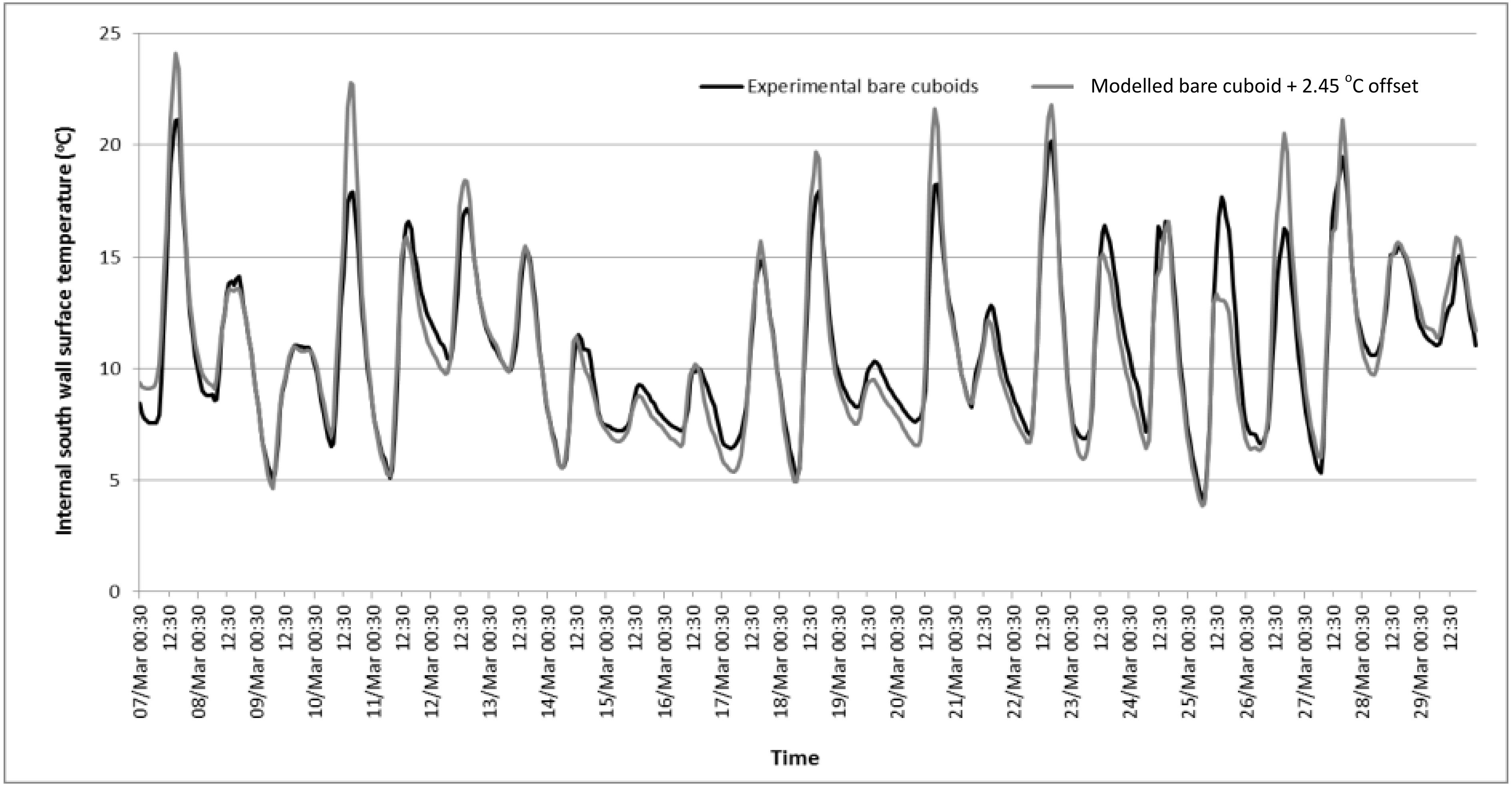

Figure 4.19 Full time series during early spring (7th-29th March 2015) where the simulated data (from the modelled bare cuboid) has had a vertical offset of 2.45 °C added, showing the impact of the offset on trend matching between the experimental and simulated internal wall surface temperatures of the bare brick cuboids versus time

4.3.4 '*Hedera* min' covered cuboid simulated during early spring

When the *Hedera*-covered modelled building was simulated in early spring and compared to the data from the experimental cuboids, there was also no phase shift between the data sets. The simulated results, however, constantly under-estimated the internal temperature of the brick cuboids (Figure 4.20, mean standard deviation ± 1.74 ^{o}C and absolute percentage difference 23.1% between the simulated and experimental internal temperatures) and had a much weaker correlation to the experimental data (R^2 = 0.775). The mean standard deviation between the simulated and experimental internal temperatures of the *Hedera*-covered cuboids was greater than the mean standard deviation of the internal temperatures within the experimental *Hedera*-covered cuboids which was ± 0.70 ^{o}C.

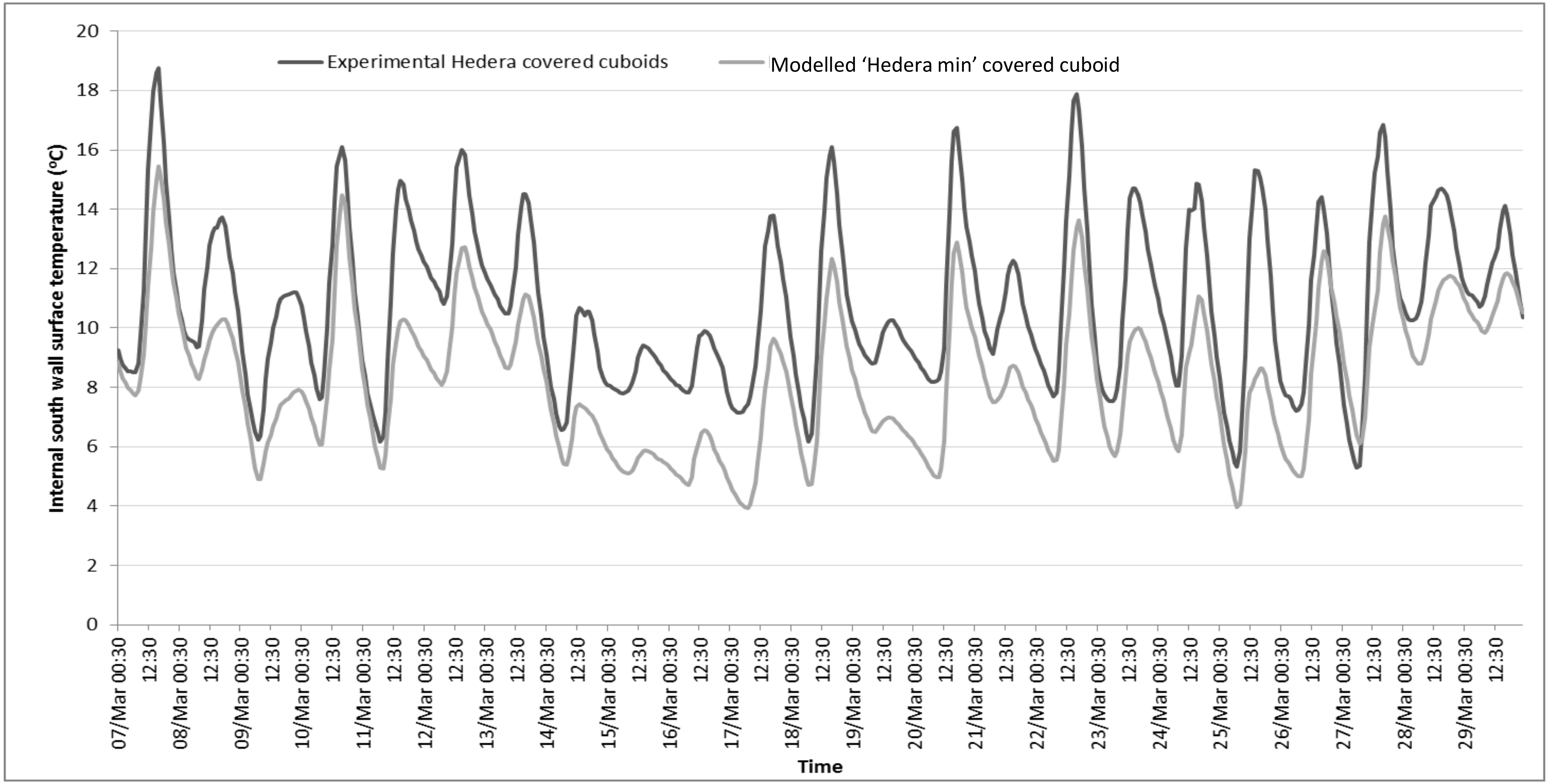

Figure 4.20 Full time series during early spring (7th-29th March 2015) for the *Hedera*-covered cuboids; showing variable matching between the internal wall surface temperatures of the experimental *Hedera*-covered cuboids and those with the '*Hedera*-min' layer simulated versus time

There was a vertical offset between the simulated and experimental data of 2.4 ^{o}C, which was applied manually to the simulated values. With the applied offset (Figure 4.21), the mean standard deviation was ± 0.73 ^{o}C and absolute percentage difference was 10.1%, between the data sets. To investigate the probable causes of the difference in overall accuracy of the simulated compared to the experimental internal temperatures, the effect of mortaring the cuboids before measuring the internal temperature was considered. The plants had been disturbed during the building mortaring in January 2015 (see section 4.2.4); therefore, a reason for the weaker correlation between the experimental and simulated data sets may have been a difference in the quality of the plant layer (compared to the summer experiment), so this concept was tested. As it was likely that the overall density of the plant-layer was reduced by the disturbance (though not measured at the time), as a proxy for the damage to the plants, the density of the '*Hedera* min' layer was reduced to half (24 kgm^{-3}) and the thickness of the layer was reduced by 50 mm to 150 mm. The simulated data provided an improved correlation between the simulated and experimental data sets (R^2 = 0.830), and manually applying a 2.4 ^{o}C vertical offset to the simulated data improved the standard deviation and absolute percentage difference between the data sets (without offset, mean standard deviation and absolute percentage difference was ± 1.72 ^{o}C and 23.5% respectively, and with offset ± 0.63 ^{o}C and 8.7% respectively). The vertical offset may have required, in part, due to the minimal heating used experimentally but not modelled in the cuboids. The reduction in standard deviation and absolute percentage difference indicates that the difference between the experimental and simulated data for the *Hedera*-covered cuboids may be, at least in part, explained by differences in the quality of foliage around the experimental cuboids during the early spring.

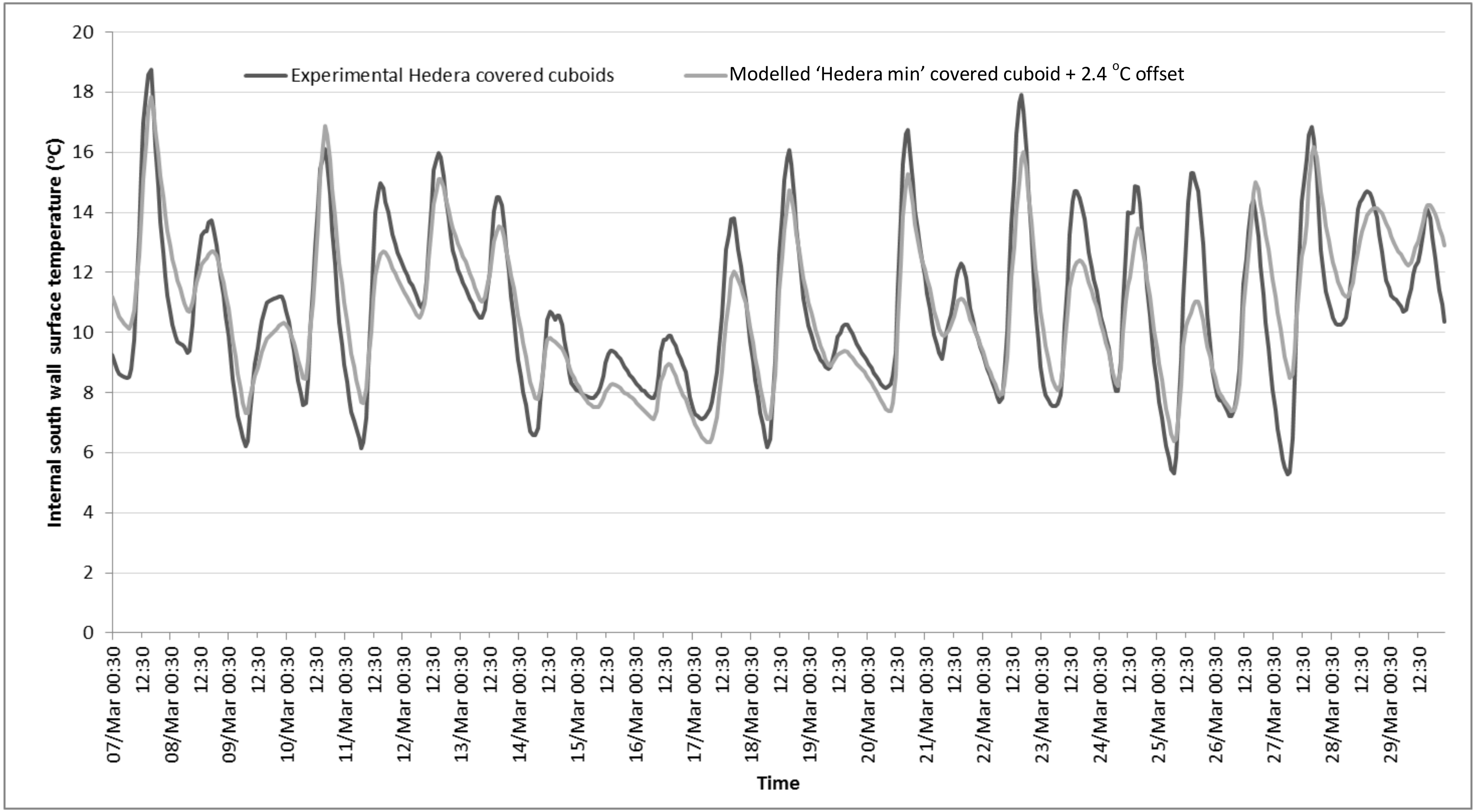

Figure 4.21 Full time series during early spring (7th-29th March 2015) for the *Hedera*-covered cuboids; showing variable matching between the internal wall surface temperatures of the experimental *Hedera*-covered cuboids and those with the '*Hedera* min' layer simulated with a 2.4 °C vertical offset added versus time

4.4 Discussion

Despite some limitations, IES software was used to simulate the internal wall surface temperature profile of the experimental bare brick cuboids very accurately (4.4% (Figure 4.12) and 7.1% (Figure 4.19) mean absolute percentage difference summer and early spring respectively, with the vertical offset). Furthermore, after developing a vegetation layer using parameters established for other plants, a simulation was performed for the '*Hedera* min' layer with accurate results as well (3.3% (Figure 4.14) and 8.7% (Figure 4.21) mean absolute percentage difference summer no offset and early spring with vertical overset, respectively). Despite the findings by Ottelé and Perini (2017), which indicated that a different thermal conductivity for summer and winter would be required, only the 'winter' thermal conductivity (equation [4.5], Table 4.5) was used for simulating the '*Hedera* min' layer during both summer and early spring.

The inaccuracies in the internal wall surface temperature profile can be considered in two parts. Firstly, those concerning the initial simulation conditions, which were likely to account for the consistent under-estimation of the temperature profile for the bare cuboid (Figures 4.5 and 4.18) and the *Hedera*-covered cuboid in early spring (Figure 4.20). These may include factors that were outside the scope of this research to model, such as the impact of the surrounding buildings (including two large glasshouses) on the experimental site, or differences between the parameters of the materials used in constructing the cuboids and those entered in the construction database. Additionally, the under-estimation by the simulation of the experimental internal south wall temperature during the early spring, especially during cooler temperatures (< 15 ^{o}C) was likely to relate to the minimal heating from the oil-based immersion heaters (see Chapter 2, section 2.6.1).

Secondly, there were inaccuracies that were situation specific or that did not apply for the full experimental period, including differences in maximum/minimum temperatures or single days that were accurately or inaccurately simulated (such as 28th June, Figures 4.10 and 4.16). These variations were more likely to be due to local temporary/changing effects, such as weather station errors, air flow patterns at 0.5 m above ground level, and the interaction between air flow and the surrounding buildings (such as providing shelter from some directions and wind tunnelling effects from others). Additionally, effects such as changes in the behaviour of the construction materials due to weather impacts, such as bricks wetted by rain that would have a higher thermal conductivity than dry bricks, could account for some of the localised (day to day/hour to hour) variation.

The apparent one hour phase shift, observed between the experimental and simulated data may have been caused by an experimental anomaly, possibly due to the data logger timings drifting (see Appendix E for further details).

4.4.1 Weather impacts

The accuracy of the simulated temperature profiles was dependent on both the weather input and the construction materials. If data unrepresentative of the local weather occurring during the experimental period was used, the impact of the construction materials broadly generated the same trends (i.e. a construction element with higher thermal diffusivity resulted in data with higher maximum and lower minimum temperatures, and lower thermal diffusivity generated smoother less variable data; see Appendix B), however, the daily temperature profiles did not match. When data increasingly representative of the local weather that occurred during the experimental period was developed then used, the simulated output matched the experimental temperature profiles more accurately. While this effect is expected, none of the other studies found in literature attempting to validate the impacts of green walls on the building envelope using IES software used weather data relating to the time and place of their experiments (Alabadla, 2013, Laparé, 2013, Xiangjing, 2011), hence the validation provided in this study has been more thorough than previous studies.

As a full weather file during the experimental period was not initially available, preliminary experiments (data not shown) showed that even unrepresentative weather files (for example, typical year data from a location close to the experiment) could be improved by replacing parameter values with data measured at the experimental location. As a minimum, these values could be replaced for the experimental period, although, a full year of data was preferable. The greatest impact came from replacing the dry bulb temperature and RH or wet bulb temperature (from which the dew point can be calculated) and if possible solar and wind data (both the diffuse and direct normal solar radiation could be estimated from the global and extra-terrestrial solar radiation).

4.4.2 Construction materials

It was important to select representative construction materials for the walls, ceiling and floor when comparing the experimental and modelled cuboids, as material alterations would change the thermal diffusivity of the construction element (see Appendix B) and hence the rate at which the vagaries of the weather (such as sunshine duration) impacted the internal environment. If the thermal diffusivity was higher for the construction materials in the simulation compared to the experimental building materials, the simulated results would over-estimate peak and under-estimate minimum temperatures, consequentially, there was less 'lag' between weather effects (such as solar gains) and the simulated effect on the internal environment.

Additionally, once the thickness of each of the construction elements was generated, alterations to the materials within them could sometimes only have minor impacts on the internal surface temperature despite changes in the U-value. This was, however, dependant on the surface being measured, such that changes to the ceiling would have smaller impacts on the internal south wall surface temperature than changes to the construction of the external wall.

4.4.3 Conclusion

Models of both bare and *Hedera*-covered cuboids were developed within IES software, and the internal south surface wall temperatures were simulated. The simulated results were within 13% difference in summer and 26% in early spring, of the measured results from the experimental buildings. While the percentage difference between the simulated and experimental results may initially appear statistically high, much of that difference was attributed to a constant difference of approximately 2 ^{o}C due to the boundary conditions set within the model.

While the model for the *Hedera*-layer did not account for evaporative cooling, the simulated results provided a similar accuracy to those of the bare cuboids, especially during early spring. This means the layer could be used to simulate the effects of *Hedera*-covering when the effects of cooling via evapotranspiration are minimal, such as during times of high RH and low solar irradiance from late autumn to early spring (Hanson, 1991, in Paulson et al., 1991).

Therefore, there are now a set of parameters for *Hedera* (SHC, density and thermal conductivity) that can be used applied to any building including domestic dwellings, to simulate the impact of plant-coverage (such as *Hedera*) on the internal temperatures during the year. Furthermore, the model could be applied to buildings that are representative of 'real world' scenarios, with heating and internal gains, to investigate the impact of plant-covering on energy use.

4.4.4 Future Work

- Generate a method of model validation using typical year weather data for instances where the local data is not available (additionally, assess the benefit of measuring some variables for example, temperature and RH).
- By measuring and validating the internal temperatures of the cuboids for an additional year and comparing that with that year's weather data, the presence or absence of the vertical

offset could be verified as well as when it appears or disappears in the *Hedera*-covered cuboids.

- Run sensitivity analyses to specify which parameters and construction specifications are critical for accurate temperature modelling.
- The *Hedera* layer developed in this project could be applied to model ‘true’ buildings to predict reductions in heating/cooling energy requirements.
- Use the measured values for RH from the experiments in Chapter 3 to validate whether IES software accurately simulates the internal RH, and then use the condensation analysis feature in IES to test whether the presence of *Hedera* altered the likelihood of condensation forming in the wall.
- The *Hedera* layer could be trialled with numerous wall configurations to find out which if any configurations were vulnerable to condensation.
- While a static plant layer may be a good starting place, others have modelled a dynamic system which may more accurately model RH effects.

Chapter Five

Ivy management: Controlling ivy attachment to wall surfaces by applying paints, metal meshes and sheets[2]

5.1 Introduction

The effects of green walls, plants growing around buildings, are well documented (Hunter et al., 2014, Pérez et al., 2014). Green walls can improve building insulation through the generation of stationary air (Ottelé, 2011) and reduced heat loss as vegetation acts as a windbreak to protect the building (Peck et al., 1999). They can also reduce wall temperature during hot periods, due to cooling from plant evapotranspiration (Cameron et al., 2014) and shading from the foliage (Ip et al., 2004, Ip et al., 2010). Other benefits include reduced variation in wall temperature (Sternberg et al., 2011a), diminished risk of freeze-thaw cycles on the exposed walls (Viles et al., 2011), and reduced wear and damage to walls by UV radiation and rain (Sternberg et al., 2010a). Green walls capture particles from the air, including 10 micron particulates (PM_{10}) and smaller (Ottelé et al., 2010, Sternberg et al., 2011a, Weerakkody et al. 2017, 2018), which have been associated with increased chance of mortality and morbidity especially for those with pre-existing respiratory and cardiac complaints (Dockery and Pope, 1994, Pekkanen et al., 2002, Timonen et al., 2005).

A number of vertical greening systems and solutions are currently in use for buildings' greening (Perini et al., 2011b). These include living walls, which are intensive systems with containers, substrate and irrigation, and green façades which are extensive systems, where plants grow in the ground or in containers and attach to the building directly or via trellises/wire/meshes. This study will focus on direct or traditional greening, a form of green façades, which employs climbing plants with suckers, attaching aerial roots, and hooks, that attach directly to the building façade. Ivy has long been used for vertical greening due to its low cost and vigorous growth. Hibberd (1872) described the bio-protective nature of ivy on historic buildings as "the vegetable keeper of historical records".

The presence of *Hedera* on buildings increases indoor temperatures in winter (Köhler, 2008), and in summer reduces indoor temperatures (Di and Wang, 1999), primarily due to shading (Cameron et al., 2014). *Hedera* can intercept driving rain (Rath et al., 1989) and reduce air flow around buildings (Perini et al., 2011a). In some circumstances, however, *Hedera* can damage walls and buildings. The

[2] This chapter was published as a paper, Thomsit-Ireland et al. (2016), for which the work was all my own.

external render has to have sufficient strength to support the weight of the plant (along with any rain/snow loading), otherwise the plant can pull or crack external plaster or render (Rath et al., 1989). Furthermore, down-pipes and gutters are at risk of detachment and blockage from ivy (Rath et al., 1989). *Hedera* can also root into and lift blocks of stone from weakened historic walls or buildings that have not been maintained (Sternberg et al., 2010a, Viles et al., 2011). Nevertheless, where the plaster was intact Rath et al. (1989) found that no damage occurred to the buildings and Viles et al. (2011) found ivy only exploited pre-existing defects in walls.

While ivy is used extensively in Europe (Köhler, 2008), if it is introduced to an area, ivy can be a highly prolific, invasive alien (Metcalfe, 2005). Although ivy has become naturalised in the United States of America, its spread and proliferation has led to ‘ivy deserts’ in some forests (Federal Interagency Committee for the Management of Noxious and Exotic Weeds & Westbrooks, 1998). In the state of Oregon both *Hedera helix* L. and *H. hibernica* (G. Kirchner) Bean and all their cultivars are considered quarantinable noxious weeds which, if kept in a garden, must be prevented from spreading or seeding (Albert, 2010).

From 1597, it was observed that *Hedera* attaches to surfaces using aerial roots (Gerard, 1597), which are adapted adventitious roots, that allow ivy to self-support and climb up surfaces (Melzer et al., 2012). A number of studies have investigated the attachment of aerial roots in *H. helix* (Zhang et al., 2008, Melzer et al., 2009). Attachment in *Hedera* is initially triggered by contact between the root tip and another surface (Melzer et al., 2010), which increases the number of aerial roots as well as their growth rate. As the aerial roots connect with a surface, adhesive is secreted from them, forming droplets on the ends of the root hairs and begins to dry on contact with the surface (Melzer et al., 2009). Additionally, the aerial roots grow to varying lengths and widths to maximize contact with the surface to which they are adhering (Melzer et al., 2009). Analysis of secretions from *H. helix* aerial roots revealed the adhesive is composed of uniform nanoparticles, approximately 70 nm in size (Zhang et al., 2008).

The force required to detach *H. helix* was measured and it was found that detachment occurs for a number of reasons: ‘substrate failure’ (the substrate breaks but the ivy attachment remains intact), ‘root failure’ (the roots break away from the substrate) or ‘stem failure’ (the stem breaks but the roots and substrate remain attached and intact; Melzer et al. (2012)). The substrate to which the ivy adhered, e.g. mortar or wood, also contributed to the detachment type that occurred (Melzer et al., 2012). In another study, an adhesive from *H. helix* failed to attach to metals (aluminium and steel), PVC, Plexiglas, glass or ceramics (Melzer et al., 2009). These two studies show that attachment force can be measured and provided guidance towards materials that prevent ivy attachment.

Both *H. helix* and *H. hibernica* have been shown to climb a number of surfaces. *H. hibernica* is often used as ground cover (Rose, 1980) as it only occasionally climbs walls and seldom trees (McAllister and Rutherford, 1990). However, some *Hedera* cultivars barely climb and are bushy or erect instead (Rose, 1996). While the attachment strength of *H. helix* has been studied in the past (Melzer et al., 2012), the difference in climbing tendencies of *H. hibernica* indicate there may be a difference in attachment adhesive and strength between species and cultivars of *Hedera*.

This study's aim was to investigate options to control the attachment of ivy aerial roots when grown as a vertical wall cover; suitable control methods could protect fixtures and fittings, such as windows and gutters. Phytotoxic substances for 'true' roots were hypothesized to also affect *Hedera*'s aerial roots; as aerial roots are a form of 'true' root and can transform into 'true' roots on contact with soil (Melzer et al., 2012). Some studies have investigated the application of chemicals to the inside of plant containers to reduce growth in 'true'/terrestrial roots through chemical root pruning. The chemicals used included emulsions of copper hydroxide, $Cu(OH)_2$ (Beeson Jr and Newton, 1992, Arnold and Struve, 1993), and/or copper carbonate, $CuCO_3$ (Struve and Rhodus, 1990, Arnold and Young, 1991) and the mixed metal salt of zinc carbonate and hydroxide (Baker et al., 1995). While root pruning methods were a starting point for developing aerial root detachment substances, this may present a problem with licensing in the UK. A commercial product, SpinOut®, created from $Cu(OH)_2$, is currently not licensed for use in the UK, so emulsions of metal salts were not considered within these experiments.

In another study, copper mesh barriers, with 1.6 mm openings, were tested against pruned regenerating cottonwood and birch roots (Wagar and Barker, 1993). Although some of the roots protruded they were restricted to the width of the opening (Wagar and Barker, 1993).

Although copper treatments were developed for 'true' roots, the techniques and materials may be transferrable to aerial roots. There is also anecdotal evidence that ivy aerial roots do not attach to galvanized fences or galvanized sheets. Solid metal sheets or meshes could be integrated into building design or attached to building walls, so both zinc sheets and copper meshes/sheets were chosen and tested in indoor and outdoor experiments.

Although there have been no studies into the interaction between anti-graffiti paints and the attachment of self-clinging climbers, the paints are likely to have suitable properties. These include hydrophobicity and oleophobicity, thus reducing the amount of available water and potentially preventing attachment. The bonding properties of the ivy adhesive were considered important when deciding which paints to test. Two types of anti-graffiti paint were chosen for experimentation, both with the ability to repel water and oil-based materials. One of the paints contained non-functional alkylsilanes (silica nanoparticles) which are both hydrophobic and lipophobic (Arkles et al., 2009). The other was a commonly used anti-graffiti paint which contained polyurethane, a petrochemical derivative. The silane-based paint may reduce attachment as it is interacting at the same spatial scale as the ivy adhesive.

Two experiments were developed to test the hypothesis that materials would prevent or reduce ivy attachment: a laboratory system with ivy cuttings and an outdoor experiment with established ivy, both with ivy growing next to cork treated with metals and paints.

5.2 Methods and statistical analysis

Details of the experimental set-up and measurement periods are provided in Chapter 2, sections 2.5.4-2.5.6 and 2.10; this chapter refers to experiment 3.

The standard deviations were calculated after averaging the results from the pseudo-replicates.

Analysis of variance (ANOVA) were performed as described in Chapter 2 section 2.9, however, in the outdoor experiment, to avoid pseudoreplication, the mean parameter values per panel were calculated from the individual stem values.

When assessing the stem breaks, the breakages were fitted to a binomial distribution, where a stem break was assigned a value of one and no stem break was assigned a zero value.

In both the laboratory and outdoor experiments there were a high number of zero values in the detachment force terms, so the analysis was broken into two sections. The likelihood of attachment was described as an odds ratio between the treatments, attachment was given the value 1 and no attachment was 0. Then a logistic regression, with a binomial distribution using the logit transformation, was performed.

To identify whether there was a significant difference between the treatments, when attachment occurred an *ad hoc* ANOVA test was performed on the data set with zero values excluded. To prevent low statistical power and an increased probability of a Type II error (false acceptance of the null hypothesis), only treatments with at least three non-zero values were considered.

5.3 Results

5.3.1 Laboratory experiment (3i)

5.3.1.1 Cuttings' growth parameters

There were significant differences in the initial stem diameter, stem weight, leaf number and aerial root number between the two species, so *H. helix* and *H. hibernica* were analysed separately. For each species there were no significant differences between the treatments in the initial parameters measured: mean stem diameter, stem weight, leaf number and aerial root number (data not shown), suggesting that the treatments did not affect the growth of cuttings. The mean initial stem diameter across treatments for *H. helix* was 1.57 ± 0.11 mm ≈ 39% smaller than *H. hibernica* at 2.47 ± 0.25 mm, and there were initially 50% more leaves and three times more aerial roots in *H. helix* than *H. hibernica* (3.2 ± 0.8 and 2.1 ± 0.2 leaves per cutting, 28 ± 15 and 9 ± 9 aerial roots per cutting, respectively).

During the experiment *H. helix* cuttings elongated more, but gained 32% less weight than *H. hibernica* (Table 5.1). There was no significant growth difference between treatments for either species and the final mean leaf area per cutting of *H. helix* was 29% less than *H. hibernica*.

Table 5.1 Mean ± SD of the final growth parameters for cuttings (*Hedera helix* and *H. hibernica*) in laboratory setting, (n = 6, treatments = 5, blocks = 10, d.f. = 16).

	Hedera helix			***Hedera hibernica***		
Parameter/ Treatment	**Length grown (mm)**	**Stem weight increase (g)**	**Final leaf surface area (cm^2)**	**Length grown (mm)**	**Stem weight increase (g)**	**Final leaf surface area (cm^2)**
Control	41 ± 9	0.33 ± 0.09	18 ± 5	24 ± 7	0.42 ± 0.14	21 ± 7
'Easy on'	38 ± 9	0.33 ± 0.04	17 ± 2	22 ± 5	0.46 ± 0.15	22 ± 5
'Pegagraff'	35 ± 4	0.33 ± 0.05	17 ± 3	24 ± 5	0.49 ± 0.10	23 ± 3
Copper	39 ± 6	0.35 ± 0.05	17 ± 1	30 ± 12	0.49 ± 0.14	24 ± 7
Zinc	36 ± 11	0.34 ± 0.09	18 ± 4	33 ± 10	0.63 ± 0.12	29 ± 5
Average across treatments	38 ± 8	0.34 ± 0.06	17 ± 3	27 ± 9	0.50 ± 0.14	24 ± 6
P value	0.722	0.966	0.813	0.421	0.237	0.293

5.3.1.2 Attachment of cuttings to wall surfaces

The number of attachment sites, assessed at the end of the experiment, was similar between species and there was no significant difference between the treatments (Table 5.2). In *H. hibernica,* however, the final mean aerial root weight per cutting for the control was significantly lower than both copper and 'Easy-on' (Table 5.2).

Both the force per attachment length and peak detachment force were measured (Table 5.2). The force per attachment length was useful where two species were being compared, as one species could have a weak force per attachment length, but a greater attachment length than the other. For example, two shoots could have the same peak detachment force e.g. 20 N, but different attachment lengths, e.g. 10 mm versus 20 mm and for the greater attachment length, the force per millimetre would only be 10 N. For industry, peak force is probably more useful as it displays the force required to remove the attached ivy from the surface (Table 5.2).

Table 5.2 Mean ± SD of the detachment parameters for cuttings (*Hedera helix* and *H. hibernica*) in laboratory setting and associated LSDs, (n = 6, treatments = 5, blocks = 10), n/a used for non-attachment, hence no length of attachment or peak attachment force. Where there was a mixed attachment response such as *H. hibernica* 'Easy on' treatment, only values from the stems that were attached were averaged, which resulted in the differing degrees of freedom shown.

Species/ Treatment	Aerial root weight (mg)		Detachment force per length of attachment ($N\ mm^{-1}$)		Length of attachment (mm)		Peak detachment force (N)	
	H. helix	*H. hibernica*	*H. helix*	*H. hibernica*	*H. helix*	*H. hibernica*	*H. helix*	*H. hibernica*
Control	9 ± 3	12 ± 6	0.18 ± 0.02	0.16 ± 0.05	23 ± 9	20 ± 6	4.0 ± 1.6	3.1 ± 1.2
'Easy on'	13 ± 8	26 ± 17	n/a	0.04 ± 0.03	n/a	12 ± 3	n/a	0.4 ± 0.2
'Pegagraff'	8 ± 3	15 ± 6	0.09 ± 0.04	0.12 ± 0.03	18 ± 6	23 ± 5	1.7 ± 0.8	2.7 ± 1.0
Copper	13 ± 5	28 ± 8	n/a	n/a	n/a	n/a	n/a	n/a
Zinc	12 ± 9	20 ± 8	n/a	n/a	n/a	n/a	n/a	n/a
P value	0.533 (d.f. = 16)	0.028 (d.f. = 16)	< .001 (d.f. = 10)	0.007 (d.f. = 6)	0.318 (d.f. = 10)	0.036 (d.f. = 6)	0.009 (d.f. = 12)	< .001 (d.f. = 10)
LSD		11	0.04	0.05		8	1.6	1.3

Although there were differences in the number of leaves, leaf surface area and stem weight between the species, their attachment response to different treatments was broadly similar (Table 5.2). Neither *H. helix* nor *H. hibernica* attached to either of the metals (Table 5.2). *H. helix* did not form an attachment to 'Easy on' whereas *H. hibernica* formed a weak bond. Both species attached to 'Pegagraff' and the detachment force per length of attachment was significantly less than the control for *H. helix* (Table 5.2). However, there was no significant difference between the control and 'Pegagraff' for *H. hibernica*. For both species, the attachment length for the control and 'Pegagraff' treatments were not significantly different (Table 5.2). In *H. hibernica* the attachment length of 'Easy on' treatment was 40% less than the control ($p = 0.036$). There was no significant difference in the detachment force required to remove *H. helix* and *H. hibernica* for the same treatment (apart from for 'Easy on' where *H. hibernica* formed a bond and *H. helix* did not). In *H. helix* there was significantly less detachment force required to remove the stems that attached to the 'Pegagraff' treatment compared to the control (Table 5.2). In *H. hibernica,* however, the detachment force between the 'Pegagraff' treatment and the control was similar.

5.3.2 Outdoor experiment (3ii)

5.3.2.1 Growth of ivy plants against wall treatments

There was no significant difference in the measured growth parameters (dry stem biomass, stem length, and diameter) between the treatments, suggesting that the treatments did not affect the growth of the ivy shoots (Table 5.3).

Table 5.3 Mean ± SD of the final growth parameters of the outdoor field trial (*H. helix* 'Glacier' shoots grown next to cork covered in three treatments). Data are means of between 9 and 20 shoots per section (n = 6, treatment = 3, blocks = 3, d.f. = 13).

Species/ Treatment	Stem biomass (g)	Stem length (mm)	Stem diameter (mm)
Control	0.56 ± 0.17	220 ± 35	2.42 ± 0.35
'Easy on'	0.68 ± 0.27	261 ± 81	2.49 ± 0.35
Copper	0.63 ± 0.22	220 ± 38	2.62 ± 0.43
P value	0.349	0.224	0.11

5.3.2.2 Attachment of ivy to wall treatments

There was no difference between treatments in aerial root biomass (Table 5.4). As these values represent the mean root biomass per panel, the percentage of individual stem attachments has been included to highlight that the mean values for 'Easy on' include 30 ± 34 % zero values where the stems did not attach. There was a significant, seven-fold increase in number of stem breaks in the control treatment versus 'Easy on' (Table 5.4). Thus 49 ± 17 % of the time the maximum detachment force for the control was greater than the strength of the ivy stem; however that only occurred in 7 ± 9 % of the cases for 'Easy on'. Both the peak detachment force and the detachment force per length of attachment showed that significantly more force was required to detach the stems from the control than from 'Easy on'. The shoots on copper formed no attachment (Table 5.4).

Table 5.4 Mean ± SD of the final detachment parameters of the outdoor field trial (*H. helix* 'Glacier' shoots grown next to cork covered with three treatments), and associated LSDs. Data are means of between 9 and 20 shoots per panel, (n = 6, treatments = 3 and blocks = 3). As no stems attached to copper, n/a was used as there are no values for detachment or stem break, and only non-zero values were analysed with the ANOVA, hence the different degrees of freedom shown.

	Dry aerial root biomass (g)	Percentage of attached stems (%)	Stem break (%)	Peak detachment force (N)	Detachment force per attachment length (N mm^{-1})
Control	0.07 ± 0.02	100 ± 0	49 ± 17	23 ± 7	0.20 ± 0.06
'Easy on'	0.12 ± 0.07	70 ± 34	7 ± 9	10 ± 7	0.05 ± 0.05
Copper	0.08 ± 0.05	0 ± 0	n/a	n/a	n/a
P value	0.06 (d.f. = 13)		< .001 (d.f. = 8)	0.001 (d.f. = 8)	0.002 (d.f. = 8)
LSD			0.15	6.12	0.08

5.4 Discussion

Results from the laboratory experiment show that *Hedera helix* had thinner stems, with more, smaller-sized leaves, which weighed less than the stems and leaves of *H. hibernica*. However, *H. helix* produced significantly more aerial roots per stem and attached to surfaces easier than *H. hibernica*. The wall treatments did not significantly influence the measured growth parameters of the cuttings in either species. While this experiment indicated that *H. hibernica* was the slower growing species, in field experiments performed by McAllister and Rutherford (1990) *H. hibernica* was found to be a faster-growing and more vigorous plant. This suggests that the cuttings may behave differently to the whole plant. Some of the other findings such as the smaller leaves (in *H. helix*) and thicker stems (in *H. hibernica*) have been described before (McAllister and Rutherford, 1990).

Both species responded comparably to the wall treatments. Zinc and copper prevented attachment and 'Easy on' partially and fully prevented attachment in *H. hibernica* and *H. helix* respectively. Both species formed a bond with 'Pegagraff'; however, in *H. helix* the bond was significantly less than the control, and for *H. hibernica* the bond strength was similar to the control. This may indicate a difference in the adhesive composition between species. 'Easy on' produced the greatest reduction in attachment of the anti-graffiti paints tested. Melzer et al. (2009) suggested that aerial roots in *H. helix* were unable to attach to aluminium or steel due to the minimal pore size of metals or an unreactive surface preventing adhesive bonding. In the experiment, it may be due to the phytotoxicity of zinc and copper. To elucidate the exact cause of the adhesion or prevention thereof, further studies would be required. The technical data suggest that many industrial tests have been performed on 'Easy on' but some clarification as to water permeability and building 'breathability' would be useful before extensive use of this product to aid ivy management around walls.

The aerial roots' weight at the end of the experiment was significantly greater for the copper and 'Easy on' treatments than the control in *H. hibernica* (Table 5.2). This was probably because the aerial roots that adhered to the treated cork dried out and were frequently left attached to the cork due to the strength of their adhesive. Therefore the aerial root weight in the unattached treatments indicate that the cuttings were growing healthily and producing large numbers of aerial roots even when the cuttings did not attach.

There was only a significant difference in the peak attachment strength between the two species for the 'Easy on' treatment as *H. hibernica* formed a bond where *H. helix* did not. This may indicate a difference in adhesive composition between *H. helix* and *H. hibernica* which could warrant additional investigation. Neither species attached to the metals, indicating the metals are a reliable choice to prevent attachment; however, their cost may deter use.

In the outdoor experiment, the treatments did not significantly influence the measured growth parameters of the shoots growing over them, indicating that plants were not affected by the treatments. The main differences between treatments came from the extent of the attachment. This supported the results of the laboratory experiment and, additionally showed that 60# copper mesh prevented aerial root attachment. While ‘Easy on’ still showed a significant decrease in root attachment compared to the control, it was not as effective as copper *in situ*, indicating that the anti-graffiti paint ‘Easy on’ may need some form of additional treatment/control in order to achieve full detachment.

In the experiment, the treatments prevented attachment over the treated area, but the ivy was then able to attach to the wall above the treated area. This indicates that further work is required to prevent ivy attaching higher up and continuing to cause complications.

5.5 Key points

- Under laboratory and outdoor conditions, zinc and copper sheets, copper mesh and silane-based anti-graffiti paint all prevented or severely weakened ivy attachment to cork; which strongly attached to the cork when it was not treated. While cork is not a true replica of a brick and mortar wall, the treatments (metal sheets/meshes and silane based anti-graffiti paint) may be used on buildings.
- It is important to reduce the gap between metal sheeting and wall, as ivy will climb under the mesh or behind the sheet if there is an opportunity; which is not a problem for the silane-based paint however, it does not fully stop attachment. Cork is a comparatively smooth surface, and with the additional grooves in bricks, the protection provided by the silane based paint may not be enough to prevent attachment.
- This work highlights some options for ivy control and management on buildings, providing methods to reduce the opportunity for ivy to creep into gutters or windows. From a basic cost comparison, the silane-based anti-graffiti paint was the cheapest solution.
- Copper and zinc could be used to manage ivy around vulnerable areas. However, as ‘Easy on’ is a clear paint it would be the most discrete deterrent, with the least visual impact. Providing it did not adversely affect the building, such as trapping moisture in the masonry, this would be the treatment to be investigated further.

Chapter Six

Ivy management: The impact of container size and water stress on plant growth and production of aerial roots in whole plants of *Hedera hibernica*

6.1 Introduction

Hedera attaches to the surfaces that it grows up using aerial roots (a form of adventitious root). It can, however, cause damage to buildings, especially around guttering and roof tiles (see Chapter 1 section 1.3.1), therefore requiring regular pruning. Methods were investigated to reduce *Hedera* management requirements by weakening attachment through reducing the shoot length or aerial root number.

Root restriction and water deficit have both been found to reduce above ground biomass in terms of leaf number, shoot length, and plant height (Richards and Rowe, 1977, Bradford and Hsiao, 1982, Ismail and Davies, 1998, Osório et al., 1998, Hojati et al., 2011). Those findings were complemented by studies which report that for many plants reducing root restriction and ensuring a well-watered regime, increased above ground plant biomass and leaf number (NeSmith and Duval, 1998, Poorter et al., 2012, Dambreville et al., 2016). The impacts of root restriction and water deficit on above ground biomass appear to depend on root confinement time, species, and container size.

A factor implicated in reduced above ground biomass production in some studies of root restriction in traditional growing systems is water deficit due to use of small containers (Ray and Sinclair, 1998). The same effect has, however, also been observed in hydroponically grown plants provided with sufficient water and nutrients (Richards and Rowe, 1977, Peterson et al., 1991, Kharkina et al., 1999). This implies the involvement of factors beyond water deficit alone.

In some species, adventitious root growth decreased during water deficit, though this finding was not universal among adventitious root producing plants (Stevenson and Laidlaw, 1985, Westgate and Boyer, 1985, Sharp et al., 2004, Yang et al., 2004). Furthermore, in several species, adventitious root growth tended to increase during extended periods of root restriction (Peterson et al., 1991, Kharkina et al., 1999). This indicates that adventitious roots sometimes elongate to take advantage of local water sources, even during water deficit.

The preliminary studies of *Hedera* showed that with increasing shoot length the number of aerial roots increased. Therefore if root restriction and water deficit have been observed to reduce shoot length in other plants, the total number of aerial roots available for attachment in *Hedera* should also decrease under these circumstances, thus reducing its capacity to attach to surfaces. Conversely, as root restriction and water deficit have been found to increase adventitious root emergence and growth in other plants, such management strategies may rebound, therefore this warrants investigation in *Hedera*.

There are some problems involved in predicting whether the reduction of the shoot growth would lead to a weakening of *Hedera* attachment. Anecdotal evidence suggests that, while some support must ultimately be required, *Hedera* can grow a significant distance unsupported in an attempt to find a surface to which it can attach (Figure 6.1). Additionally, as was observed in field tests (detailed in Chapter 5, section 5.3.2), established *Hedera helix* shoots were covered in aerial root attachment sites along approximately half their length (per 220 mm shoot length, the mean attachment length was 115 mm, or 44%). Where attachment strength was, however, reduced due to anti-graffiti paint a greater proportion of shoot length bore adventitious roots (200 mm attachment length for 260 mm shoot length, or 77%), hence, attachment length does not necessarily correlate with strength.

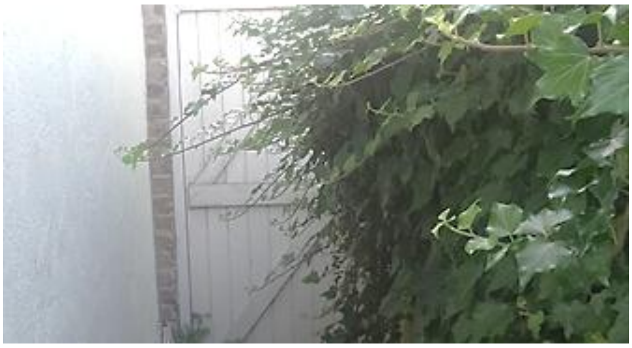

Figure 6.1 *Hedera helix* stems growing across a 1 m gap with 600 mm unsupported growth

Furthermore, *Hedera* shoots still gain a certain amount of support from contact with a surface; shoots have been observed to climb around a ledge, without any visible attachment, and reattach on the other side (Figure 6.2).

Figure 6.2 *Hedera helix* growing round a 300 mm ledge to climb back to the wall

Some of the *H. helix* stems (from the same plant) that climbed under the ledge, however, later fell away to search for new attachment surfaces (Figure 6.3a). The extent to which such strategies are effective appears to be species dependent; for example, *H. colchica* 'Sulphur Heart', which produces thicker stems and heavier leaves than *H. helix*, was unable to remain attached when climbing under ledges treated with repellent materials (e.g. copper, Figure 6.3b).

Figure 6.3 L-R: *Hedera helix* (a) and *H. colchica* (b) falling away after climbing under a ledge

While a reduction in shoot length or aerial root number in *Hedera* varieties would not guarantee a reduction in attachment strength, it does indicate fewer attachment opportunities.

6.2 Methods and statistical analysis

The methods are summarised in section 2.10 experiment 4.

The standard deviations were calculated per treatment per date of measurement.

Prior to statistical analysis, growth data were log-transformed to minimise residuals; raw data is included here to assist reader understanding. Additionally, as there were no significant interactions between watering regime and container size, these data were grouped into 'large' and 'small' containers and then compared with one-way ANOVAs. In the last two graphs of aerial root number over time (Figures 6.8 and 6.9) the least significant differences of the means (LSDs) have been omitted as they are un-necessary in graphs illustrative of the practical implications of the combined effects of root restriction and water deficit on *Hedera.*

6.3 Results

6.3.1 Substrate moisture content (SMC)

Between 4th November 2013 and 4th March 2014 the mean SMCs measured in each of the treatments: ('large stressed', 'large watered', 'small stressed' and 'small watered') were 0.15, 0.26, 0.13, and 0.46 m^3m^{-3} respectively (Figure 6.4). From day 15, SMCs differed significantly between all the treatments (p = 0.001); a state that continued for the duration of the experiment, except on day 87, where there was no significant difference between the treatments (Figure 6.4).

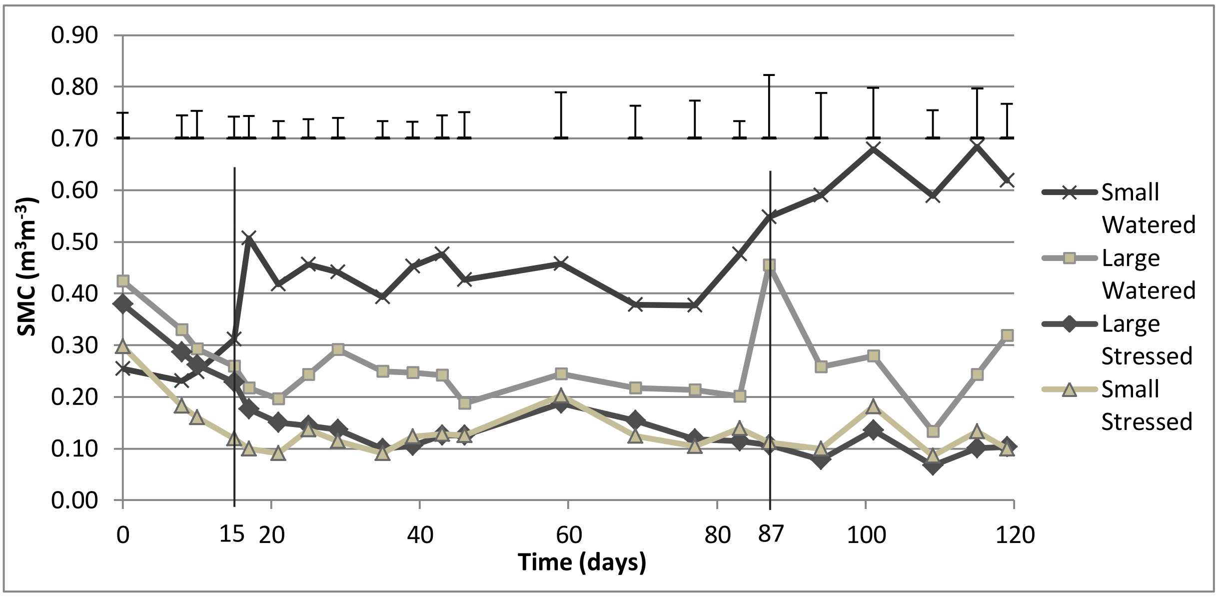

Figure 6.4 Substrate moisture content (SMC) versus time for all treatments, watering and root restriction, n=5 per treatment, between 5th November 2013, and 4th March 2014. Large vertical lines represent the points at 15 and 87 days. The smaller vertical lines represent LSD between treatment means, on each measurement occasion.

6.3.2 Effects of container size and watering regime on final shoot length, leaf number, and root number

There was a marginally non-significant effect of water deficit on the mean final shoot length of plants grown in large containers (p = 0.053), which compared to a significant effect on those grown in small containers (p < .001; Figure 6.5). The plants grown in large stressed containers had mean final shoot lengths 23% shorter than those grown in the well-watered containers (1583 ± 322 mm (large well-watered) and 1212 ± 156 mm (large stressed) mean final shoot lengths; Figure 6.5). The effect was, however, much more pronounced in smaller containers; plants grown in the small stressed containers had mean final shoot lengths 59% shorter than those grown in the small well-watered containers (1317 ± 42 mm (small well-watered) and 546 ± 38 mm (small stressed) mean final shoot lengths; Figure 6.5).

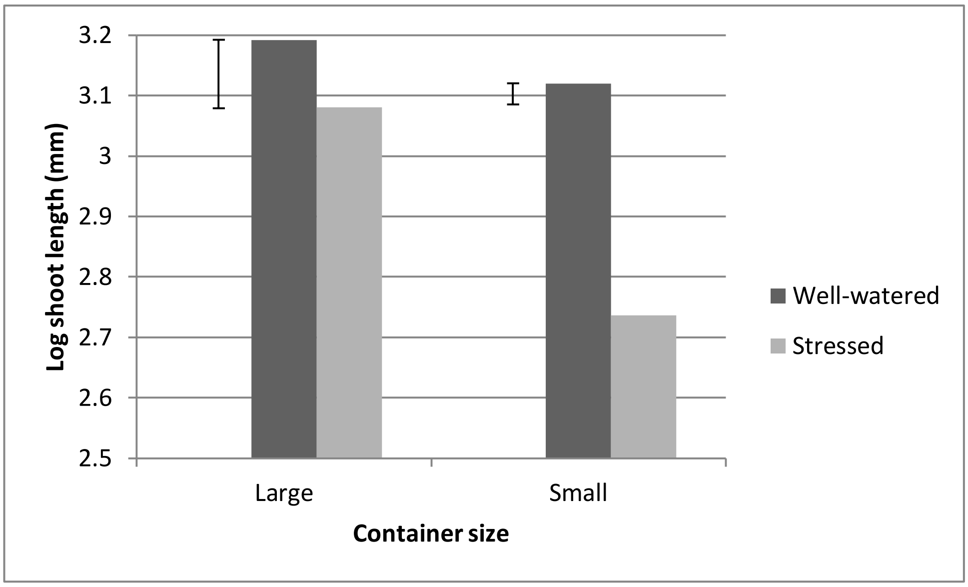

Figure 6.5 Log. mean shoot lengths on 04/03/14 (small containers pot bound), versus the container size, vertical lines represent the LSD between treatment means of the well-watered and stressed watering regimes, n=5 per treatment.

There was no significant effect of watering regime on mean final leaf number for plants grown in large containers ($p = 0.311$), compared to a significant effect for those grown in small containers ($p < .001$; Figure 6.6). The plants grown in small stressed containers had 57% fewer leaves during the final measurement than those grown in small well-watered containers (56 ± 15 (small well-watered) and 24 ± 4 (small stressed) leaves respectively).

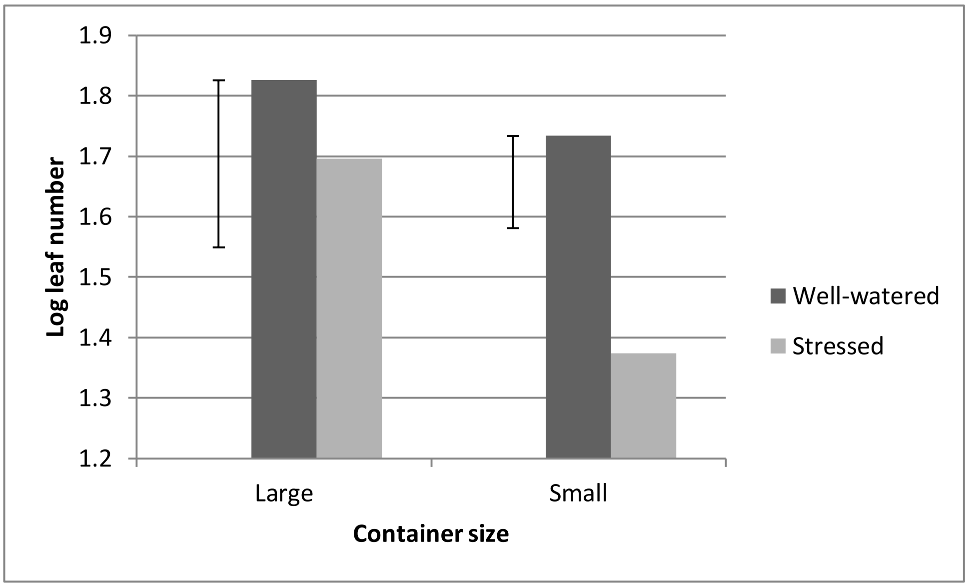

Figure 6.6 Log. mean leaf number on 04/03/14 versus the container size, vertical lines represent the LSD between treatment means of the well-watered and stressed watering regimes, n=5.

Mean final aerial root abundance was significantly reduced by water restriction for both container sizes ($p = 0.01$ for large containers, $p < .001$ for small containers; Figure 6.7). The mean final aerial root number on plants grown in large stressed containers was 51% of that found on those grown in well-watered containers (608 ± 178 (large well-watered) and 300 ± 96 (large stressed) aerial roots). However, an even greater reduction (82%) was observed between the mean final aerial root number on plants grown in the small stressed compared to well-watered containers (377 ± 179 (small well-watered) and 68 ± 13 (small stressed) aerial roots, Figure 6.7).

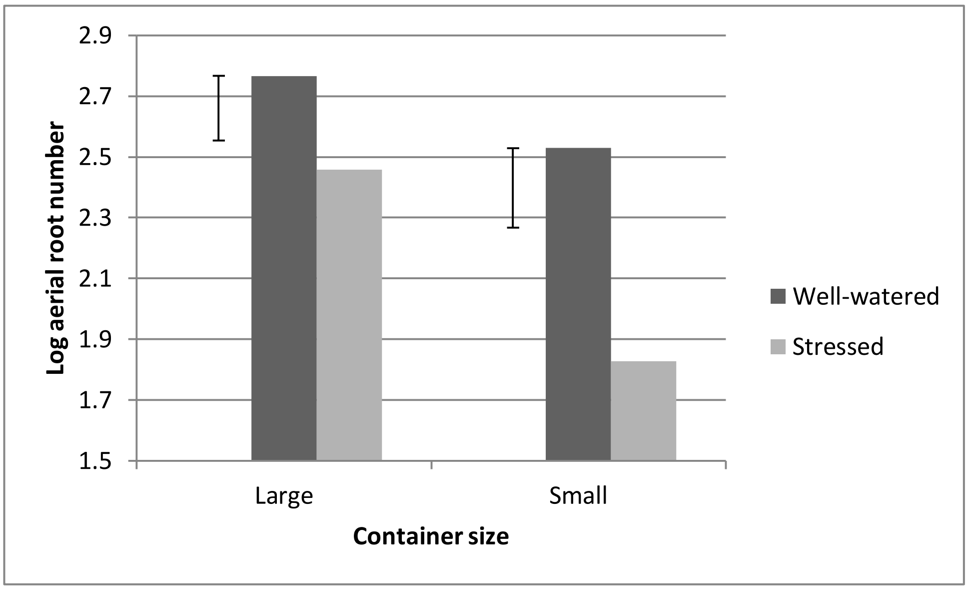

Figure 6.7 Log. mean aerial root number on 04/03/14 versus the container size, the vertical lines represent LSD between treatment means of the well-watered and stressed watering regimes, n=5

In combination, root restriction and water deficit reduced the number of aerial roots per millimetre of shoot length to a third of the control values (i.e. plants grown in large well-watered containers; Figure 6.8). There was, however, no significant difference between the treatments in terms of the number of aerial roots per leaf and millimetre of shoot length, indicating the importance of leaf number in controlling aerial root production (Figure 6.9).

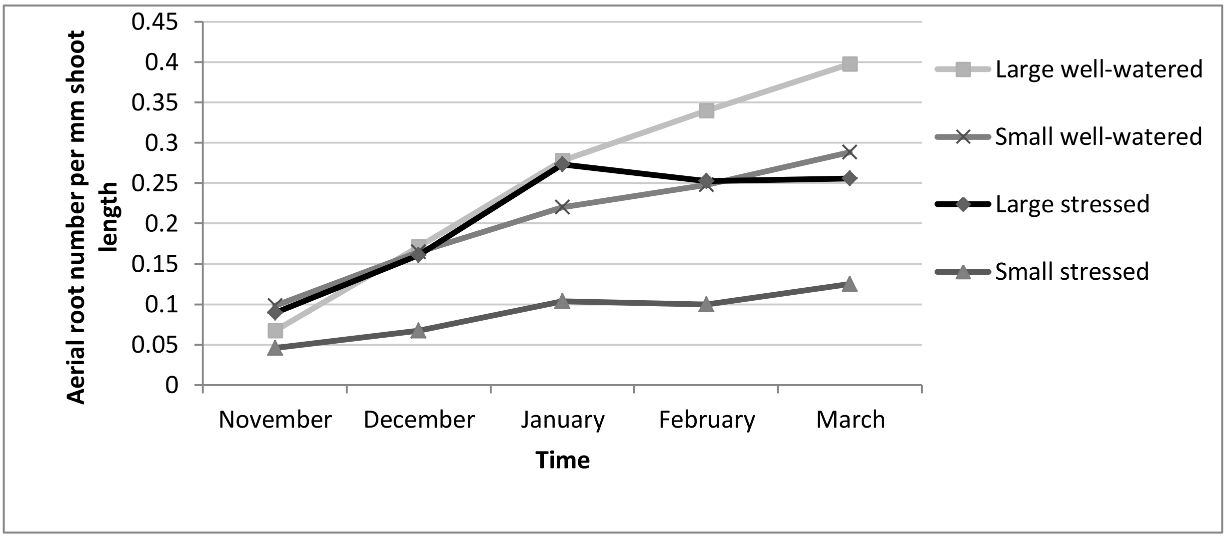

Figure 6.8 Mean aerial root number per shoot length over time

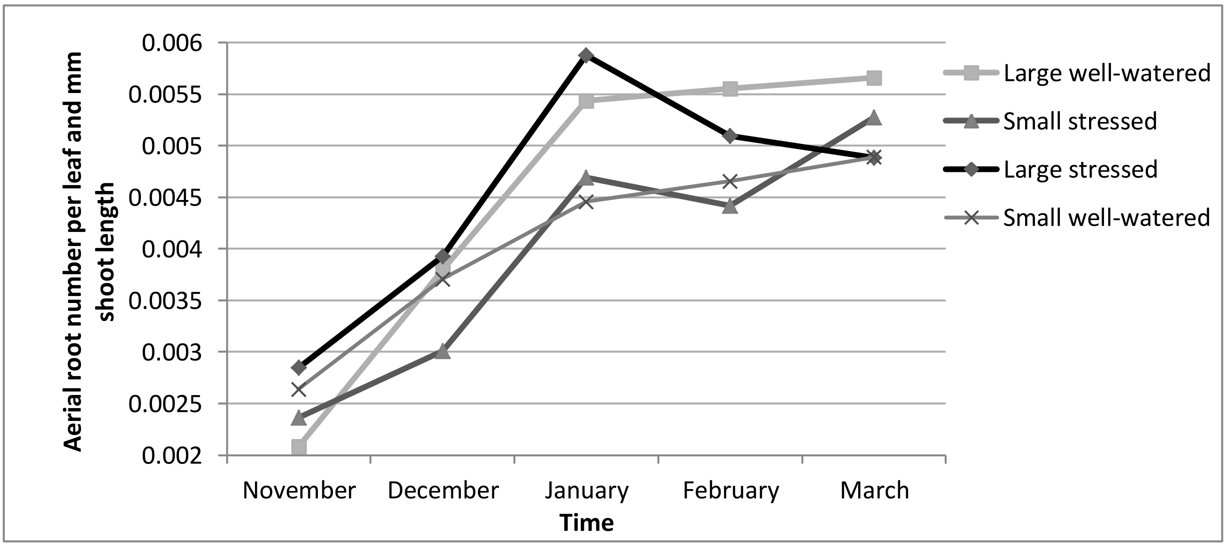

Figure 6.9 Mean aerial root number per leaf and shoot length over time

6.4 Discussion

There were no differences in *H. hibernica* shoot length, leaf number and aerial root number between sizes of well-watered containers, suggesting that root restriction alone would not prove sufficient to manage *Hedera* growth. Studies on other species, however, have shown that root restriction, without additional water deficit can be instrumental in reducing above-ground vegetative growth (Richards and Rowe, 1977, Peterson et al., 1991, Ismail and Davies, 1998, Kharkina et al., 1999). For example, Kharkina et al. (1999) showed that reducing the container size in *Cucumis sativus* (cucumber) reduced above ground biomass by 79%.

The resistance to root restriction observed in *Hedera* may be a result of its pre-anthropic niches; growing up against trees and cliffs (McAllister and Marshall, 2017). In these situations it is likely that tree roots and stony ground would provide very limited space for rooting and therefore that selection pressures will have affected *Hedera's* evolution accordingly. This same resistance, however, whilst not useful for management, does indicate that *Hedera* is a useful plant for structural greening in urban areas, where soil is often compacted (Dunnett and Kingsbury, 2005; Rose, 1980).

While a significant reduction in leaf number was found for both container sizes during water deficit in *Brassica napus* (oilseed rape/rapeseed) plants (Dambreville et al., 2016), a reduction in leaf number was only found in the small stressed containers in this experiment. This suggests that, in *Hedera* at least, prolonged water deficit alone was not sufficient to cause a reduction in leaf number. Effects on shoot length are, however, rather different, matching the reductions seen in other species; in the case of the water deficit treatment applied to large containers, the results agreed with those observed in Hojati et al.'s 2011 study.

There may be two drought resistance strategies occurring in *Hedera,* in addition to passive mechanisms such as its low stomatal conductance (see section 3.5). During the early stages of root restriction and water deficit (before the plants became pot bound, data not shown), there was rapid shoot elongation; given that aerial roots can convert into true roots upon interaction with soil (see section 1.4.1), such a strategy may allow the plant to rapidly find new sources of water and nutrients. However, if drought and restriction conditions are prolonged (after the containers became pot bound), a second strategy may occur, where the plant diverts energy into leaf area in order to build reserves and maintain a living state until conditions improve.

The combined effect of water deficit and root restriction in *H. hibernica* was reduced above ground growth and aerial root number, which occurred because shoots were shorter, with fewer leaves and fewer aerial roots per unit length. The reduction in aerial root number indicates that, unless the qualities of *Hedera* adhesive change under water deficit and root restriction, the attachment force of shoots under root restriction and water deficit should be a third of the control shoots; however, this was not tested.

This potential reduction in attachment strength from root restriction and water deficit is greater than that generated by the use of anti-graffiti paint alone (see Chapter 5). If anti-graffiti paint were to be combined with water deficit and root restriction, the detachment force produced by *Hedera* was estimated to be reduced to around 3 N. A *Hedera* shoot, 0.5 m long weighs between 20-30 g (dependent on cultivar, those with large leaves may weigh more) and therefore required 0.3 N force to support its weight (ten times less than the reduced peak force). Nevertheless, restricting the size of planting holes for *Hedera*, or trenching naturally established plants, in combination with the application of impervious/semi-impervious ground cover to reduce water inflow and the use of anti-graffiti paint on walls would greatly lower attachment potential in *Hedera*, leading to easier management.

6.5 Practical implications

While being in 'small' (restricted) and 'stressed' (water deficient) containers impacted shoot length and number of leaves similarly, these factors had a greater effect on the number of aerial roots produced, indicating that continued root restriction and drought would reduce ivy's capacity to attach. This may indicate that after a dry summer it would be prudent to heavily prune *Hedera* with the intent of reducing the level of hazard presented to passers-by by shoot detachment under the burden of wind, rain, or snow.

Regarding *Hedera* management, root restriction and/or water deficit generate the potential to reduce the attachment strength by reducing the number of aerial rooting sites available for the vegetative growth of ivy. However, rather than weakening attachment across a whole plant as is it growing, this form of management may be better applied to established plants as a method to reduce attachment in new growth without adversely affecting established attached shoots, though this would require further research.

Chapter Seven

Sustainability and economics of green walls; policy and incentives for implementation in the UK

7.1 Introduction

Undeveloped land provides many ecosystem services, defined as “benefits human populations derive from ecosystems” (Bolund and Hunhammar, 1999). Ecosystem services protect livelihoods, developed land, and local environmental quality (e.g. sinks for air, water and land pollution and sources of biodiversity) depending on the type of habitat concerned. To protect undeveloped land and maximise the appeal of built-up areas, integrating urban green infrastructure (GI) can mitigate some of the ecosystem services lost to development. GI is defined as ‘a network of multi-functional green space, both new and existing (rural and urban), supporting natural and ecological processes which is integral to the quality of life and health of sustainable communities’, and includes greened walls, roofs, and open spaces (Department for Communities and Local Government, 2008).

The proportion of the British population living in urban areas has increased at a rate 0.04% per year since 1982; as a result 95% of people resident in England and Wales were classed as living in built-up areas by 2011 (ONS, 2011, The World Bank, 2017). Urbanisation can escalate the risks of water pollution and flooding, due to construction on flood plains, and impervious surfaces associated with developments (that increase surface water run-off), which can affect developments downstream. Additionally, water entering storm drains increases the load into rivers, increasing the risk of flooding (Arnold and Gibbons, 1996). While other forms of GI are more widely associated with the ability to reduce surface run-off (e.g. green roofs and rain gardens); vertical rain gardens have been developed which can store approximately 42 L m^{-2} (Treebox, 2014a). Additionally some green walls installed in the UK are irrigated with rainwater, thus sequestering some of the potential surface water run-off (Treebox, 2014a, ANS Global and Chambers, 2018a). Furthermore, trenches to provide soil access for plants used in green façades reduce the proportion of urban surfaces impervious to water.

Another argument for the introduction of green walls is that they mitigate the urban heat island effect (UHIE). The UHIE, which has been known to increase temperatures in London by up to 8.9 ^{o}C, is often reduced in areas near open spaces, trees and green roofs (Hall et al., 2012, Skelhorn et al., 2014, O’Malley et al., 2015); there also is some evidence that green walls may alter the local microclimate in a similar vein. While temperature reductions due to such greening are rarely felt more than 1 m away from the wall (Wong et al., 2010a, Perini et al., 2011a), there may be a collective cooling effect from multiple green walls all slightly cooling the surrounding air and reducing reflected heat from building materials (Alexandri and Jones, 2008). On a related note, green walls have been found to reduce the need for air conditioning in buildings (Pan and Chu, 2016) therefore also reducing heat exhaust from air-conditioning units (though this is less applicable in the UK).

Green walls (especially living walls with integrated insulation), may provide additional thermal insulation (Chapter 3 section 3.3.3.9) and therefore increase the internal building temperature by 2 ^{o}C (Cameron et al., 2015, Ottelé and Perini, 2017). Green walls, however, only have an effect on moderately insulated buildings (Feng and Hewage, 2014a, Olivieri et al., 2017), therefore, for maximum impact, green walls should either be integrated into the initial design (an approach which reduces material requirements) or retrofitted to older buildings which cannot be insulated by conventional methods.

Furthermore, as has recently been highlighted by several news outlets (Laville, 2017, Taylor, 2017, BBC, 2018) particulates and other vehicular emissions are currently above the WHO guidelines across the UK. Urban areas typically have higher concentrations of these emissions due to ‘street canyon’ geometry (which prevents air mixing uniformly), and higher density of vehicles (Defra, 2011, Pugh et al., 2012, Karagulian et al., 2015, WHO, 2016). Green walls have been shown to capture particulates (Bernstein et al., 2007, Ottelé et al., 2010, Sternberg et al., 2010b, Shackleton et al., 2012, Perini et al., 2017b, Weerakkody et al., 2017, Weerakkody et al., 2018) and, due to their potential applications as building façade coverage, are particularly beneficial in ‘street canyons’, especially where the height to width ratio is over 1:1 (Pugh et al., 2012). Plants capture different quantities and fractions of particulates depending on their leaf morphology, arrangement and size amongst other factors (Perini et al., 2017b, Weerakkody et al., 2017) indicating that living walls could be tailored to enhance capture rates. *Hedera* has been shown to capture a moderate number of particulates; 1.47-2.9 x 10^{10} per m^2 leaf area in heavy traffic areas (though the particulate accumulation time was not specified), but is highly pollution tolerant (Ottelé et al., 2010, Sternberg et al., 2010b, Perini et al., 2017b). Additionally, plants with high capture rates such as *Buxus sempervirens* (box, Weerakkody et al., 2018) and *Trachelospermum jasminoides* (star/confederate jasmine; Perini et al. (2017b)), could be used alongside *Hedera*, if they were to prove capable of enduring long periods in such highly polluted areas.

Using a combination of trade/industry reports, policy, and scientific information, the objectives of this chapter are to critically review and discuss the practicalities of increasing green wall uptake in the UK based on:

- Where green walls are being installed in the UK, using case studies from the five major green wall installers AnsGlobal, Scotscape, Biotecture, Treebox and Mobilane.
- Why green walls are being installed;
- A review of green wall sustainability credentials, through life cycle assessment and an exploration of the technical standards that could be used to validate future sustainability
- Barriers to green wall installation, including a review of cost-benefit analysis approaches;
- Funding sources available for green wall installation in the UK;
- Planning and policy support for generating and maintaining green infrastructure: using London as a case study;
- Options for incentivisation and mandating green wall requirements in the UK based on methods to increase green roof installation uptake across the world.

Within this chapter the term 'green wall' will be taken to encompass all forms of vertical greening schemes, namely direct greening, indirect greening, and all forms of living wall system such as modular-, geotextile-, and planter-based (see Chapter 1 section 1.1.1). When used specifically, the term 'green façade' will relate to the use of climbing plants that either attach directly or indirectly via supports to the wall; the term 'green roof' will be applied to intensive, extensive, semi-intensive green roofs, brown roofs and roof gardens (Oberndorfer et al., 2007, Rowe, 2011).

7.2 Where and why are green walls installed?

To gain a snapshot of the current green wall market, case studies were obtained from the websites of five major UK green wall installation companies: Mobilane, AnsGlobal, Scotscape, Treebox, and Biotecture (Treebox, 2014a, Treebox, 2014b, ANS Global and Chambers, 2018a, Biotecture Ltd., 2018, Mobilane UK Ltd., 2018c, Scotscape, 2018). This provided 215 case studies, accounting for at least 23,235 m^2 of green wall installations, across the UK, while this is not an unbiased sample, the case studies do provide an indication of some of the green walls installed since 2007. There were 133 case studies found for London, 4 for Wales, 2 for Scotland and 76 for the rest of England; no case studies were found relating to Northern Ireland. Only external walls were considered.

The green wall case studies were divided by building type, based on building use, to elucidate the drivers for greening. Nearly half of green wall installations in London were applied to residential (Figure 7.1); additionally installations in London for retail, hospitality and other venues (such as sports sites, and theatres) accounted for around half of the total green walls installed nationally. There were, however, more green walls installed around educational establishments across the UK than there were in London (Figure 7.1).

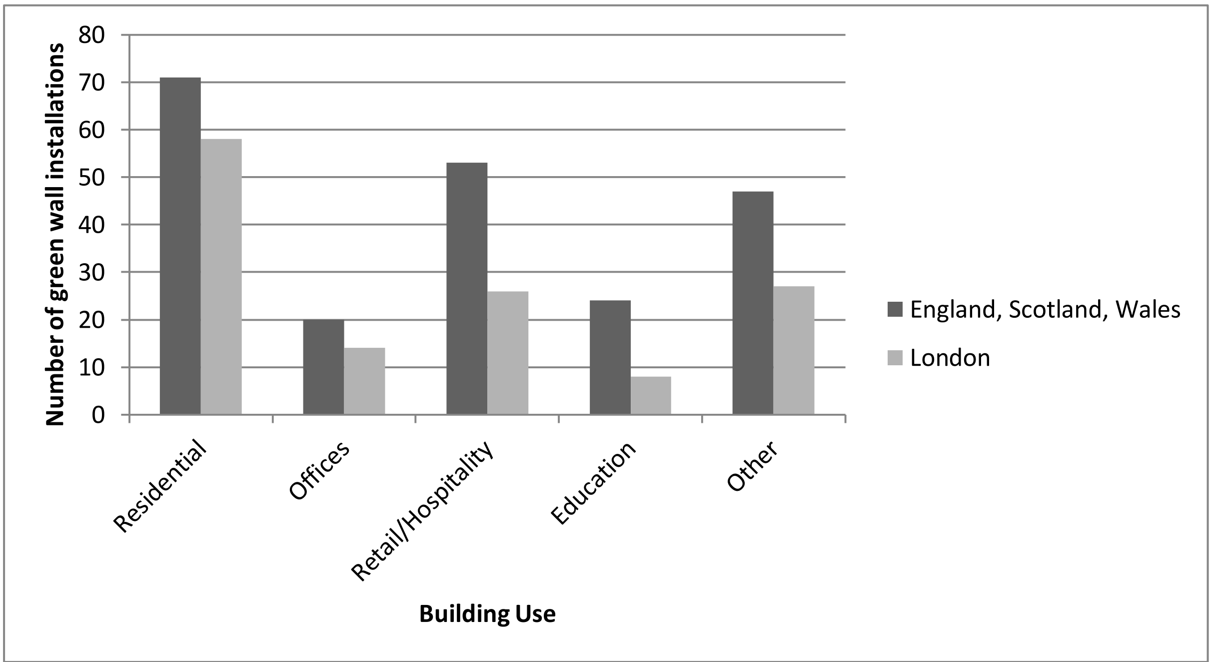

Figure 7.1 Breakdown of the 215 external green wall case studies represented on the websites of the five major green wall installation companies in the UK, Mobilane, AnsGlobal, Scotscape, Treebox, and Biotecture, of which 133 case studies related to London. The case studies were divided by building use, and other included health, events, sports and mixed use buildings.

7.2.1 Reasons for greening

When the case studies were analysed multiple drivers or reasons were often given for the installation of a green wall (although in some cases none were presented). Where multiple reasons were given, all were counted, hence from the 215 analysed case studies 347 reasons (including no information) were given, which could be broadly grouped into six categories: air quality, aesthetics, biodiversity, biophilia, sustainability and other or unknown. Drivers based on the desire to be near greenery, to soften the visual impact of building design, and so forth were referred to under the term ‘biophilia’; a concept described as an adaptive love of nature (Wilson, 1984, Joye and De Block, 2011). Aesthetic and decorative reasons were also grouped together and ‘other’ included reasons such as planning requirements and BREEAM accreditation (a sustainable building assessment system based on measures to reduce the environmental footprint (Alyami and Rezgui, 2012); Figure 7.2).

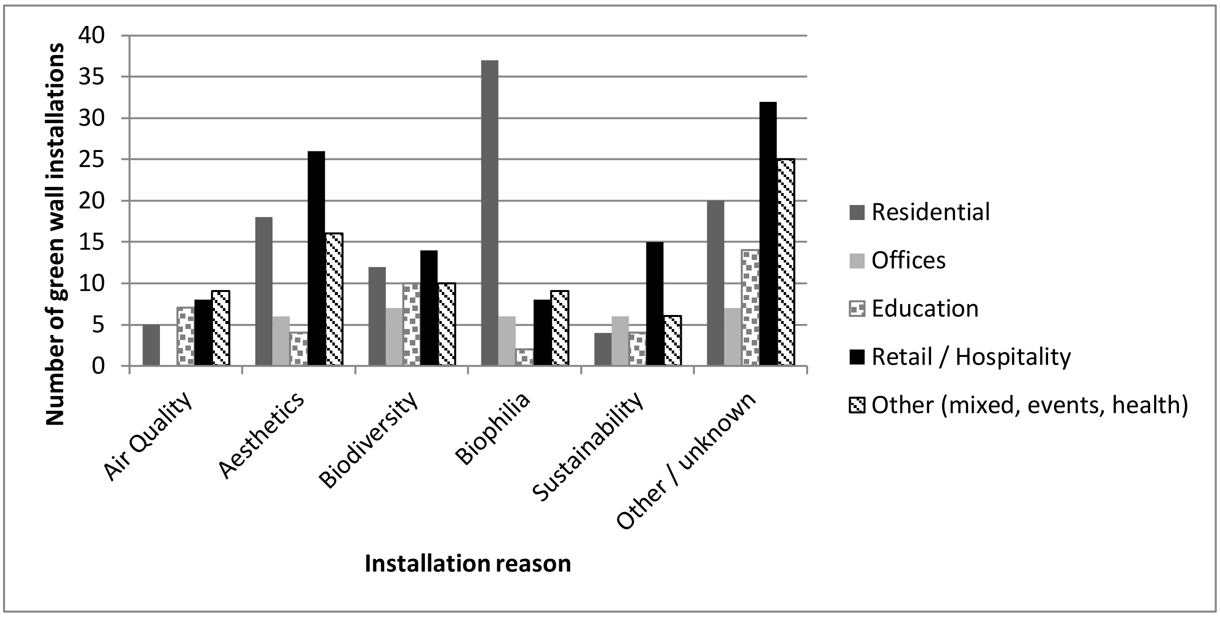

Figure 7.2 External green wall case studies (215) represented on the websites of the five major green wall installation companies in the UK, Mobilane, AnsGlobal, Scotscape, Treebox, and Biotecture. The case studies were divided by building use and the reasons given for the green wall installation.

Drivers for the adoption of green walls on commercial buildings were considered separately based on the overall use of the building (office-space vs. retail and hospitality) as their ‘needs’ are potentially different. Whereas the largest driver for installation on office buildings was, somewhat surprisingly, biodiversity, those for retail and hospitality fell into the categories of ‘aesthetics’ and ‘other’. These differing reasons for both types of commercial spaces were hypothesised to represent an attempt to improve visitor and employee wellbeing. In a study regarding the motivations of companies to adopt voluntary environmental management schemes one stated motivation was to improve connection with customers (Khanna and Anton, 2002). Anecdotally, this desire to build a brand identity may explain why there were more retail and hospitality sites with green walls than offices found within the analysed case studies. In office buildings, drivers might be focused on the desire to create iconic flagship offices, generate positive media coverage, and reduce staff turnover by improving wellbeing (personal comment).

In educational establishments, sustainability credentials were initially thought to be attained either as a result of pressure from the student body (resulting from campaigns by the NUS, university societies, and student union officials) or as part of a strategy to attract new applicants (Stafford, 2011). A study of 180 USA and Canadian Institutions of Higher Education (IHEs), however, found that the only student related factor significantly affecting the uptake of sustainability measures was the percentage of students originating from overseas or other states (the higher the percentage the higher the chance that a university adopted sustainability measures). Instead, for IHEs, pressure from alumni, faculty, and the surrounding community had more influence on the uptake of sustainability measures (Stafford, 2011). This suggests that while current students had minimal impact on the tendency of universities to install sustainability measures, permanent staff were able to influence tangible changes. This may be as a result of greater emotional investment in the community by these stakeholders due to their longer residence times. Furthermore, sustainability was considered a 'luxury good' with measures typically installed by wealthier, larger IHEs, though wealth and size were not drivers for purely symbolic sustainability gestures (Stafford, 2011).

Based on the case studies available, drivers for the installation of green walls on residences, particularly in central London, were hypothesised to be the small garden space on average available for residences in the capital and their high property values. This resulted in a combination of affluent households with a desire for a more natural setting (biophilia) which was conducive to green wall installation. The desire to remain 'on trend' may also play a role, though this is hard to verify.

The green wall industry appears to be in good health and when annual installation numbers are examined, the UK industry seems to be growing between 2007 and 2017 (which was backed by industry reports (Cosgrove, 2017) and Figure 7.3). There was, however, a little shrinkage over 2015/16, which may be a factor of which case studies were exhibited on the websites (Figure 7.3). The installation numbers for 2017, however, appear to be increasing again indicating a growth in demand, so it would appear that the industry is far from having fulfilled its full potential; there are plenty of opportunities for growth.

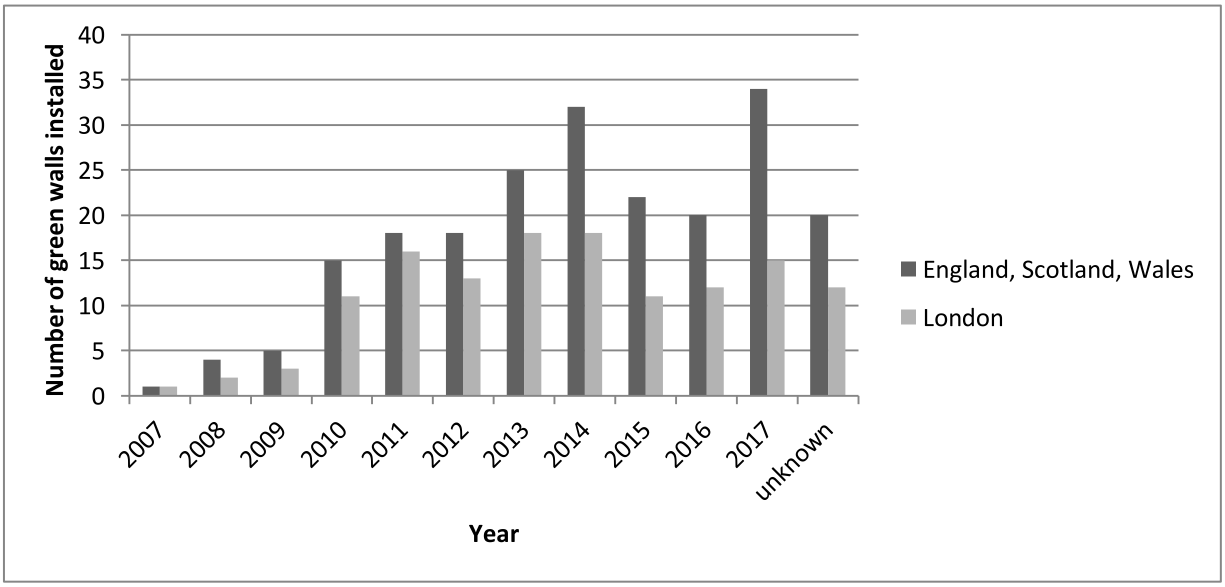

Figure 7.3 External green wall case studies (215) represented on the websites of the five major green wall installation companies in the UK, Mobilane, AnsGlobal, Scotscape, Treebox, and Biotecture, of which 133 relate to London. The case studies are divided by installations per year, with a subdivision for London.

7.3 Green wall sustainability

A life cycle assessment (LCA) is a methodology used to assess the environmental impact, via multiple categories such as global warming, eco-toxicity, and resource depletion (Ottelé et al., 2011, Curran, 2013), of a product throughout its 'life' (during manufacture, transport, use and disposal phases). It is sometimes known as 'cradle-to-grave' assessment or, in cases where the product can be fully recycled/reused, 'cradle-to-cradle' assessment (Hunt and Franklin, 1974). An LCA seeks to analyse the energy and polluting emissions generated through the manufacture, transportation, assembly, use, disposal of components, and ultimately the completed system (e.g. for a green wall). This methodology highlights particularly energy intensive/polluting stages or components of a system, which can then be targeted to increase sustainability (Ottelé et al., 2011). It also identifies areas in which environmental impact can be significantly reduced with minimal expenditure (Horne et al., 2009).

It is important to assess the sustainability of green walls in order to determine the extent to which the claims made of their properties are accurate. LCAs offer an established method of doing this and a standardised framework for comparing multiple approaches to the concept. This system also allows the industry to identify areas that could be targeted for further improvement.

There are, however, several limitations to LCAs as an approach (Ayres, 1995), including the complexity of the methodology, the assumptions made when generating the LCA may not reflect 'real life' practises, many of the inputs are based on databases using averaged hypothetical values, which means different databases may produce inputs with values orders of magnitude apart (Ayres, 1995, Owens, 1997, Reap et al., 2008a). Additionally, the scope and assumptions can alter the results, hence agreed upon limitations require establishment for realistic comparisons between companies/products. Finally, if 'benefits' are used to offset environmental costs (as can be done with green walls as part of a building), the proposed 'benefits' may be based on data from simulations, which adds a further layer of uncertainty (see Ottelé et al. (2011), and Pan and Chu (2016)).

Despite these limitations LCAs still offer a solid foundation to evaluate which stages in a product's life cycle are likely to have the greatest environmental impact. Therefore this section will discuss the factors required to generate a robust LCA for evaluating British green wall installations, then review the outputs of previous LCAs performed on structural greening systems.

7.3.1 Proposed standard for a green wall LCA

There are several international standards for LCA; ISO 14040:2006 and ISO 14044:2006 (ISO, 2006a, ISO, 2006b) that could be used to generate an assessment of the impact of green walls in the UK. These standards require any LCA to contain main four phases: scoping, inventory, eco-profiling and interpretation (Ayres, 1995); see Chapter 1 section 1.7.2 for further details.

Firstly, a functional unit first needs to be defined; this is the quantified part of the system that will be considered within the LCA. Within the context of green walls the functional unit needs to be considered as part of a larger installation, for example, a 1 m^2 functional unit within a larger wall such as 100 m^2, as this allows for services that would be used on a larger wall (such as water pumps) to be applied proportionally per square metre. A 1 m^2 functional unit has been used by several studies (Ottelé et al., 2011, Feng and Hewage, 2014b, Natarajan et al., 2015). There are, however, several options available for the size of the fictitious green wall: data from the installation case studies show that 21% of all installations are under 30 m^2 but also that 30% of the 'walls' are between 75 and 125 m^2, which may imply a divergence in size between residential and commercial installations. Therefore, a good argument could be made for developing two standards; one for residential and one for commercial use, with a functional unit of 1 m^2 within two differently sized fictitious walls of 30 m^2 and 100 m^2 respectively. This would allow for the analysis of the different scales, inputs, and impacts of these categories of green wall. Furthermore, a 100 m^2 fictitious wall was used in the LCA by Ottelé et al. (2011) and there is a costing for living walls based on a threshold of 35 m^2 (Langdon, 2014).

It is also necessary to establish where in a product or service's life cycle the assessment should begin and end (the assessment period), for example, the environmental impact of green wall plants could be examined from either the seed, which would include the substrate used for planting (if access to data from nurseries were available) or the point at which the fully developed plants are installed into the wall system. While it may reduce model complexity to begin at a later point, there is a good argument (both in terms of model accuracy and industry transparency) to be made in favour of greater diligence, and starting the LCA at the seed stage for the plant, especially for cases such as plant nursery inputs which are frequently monitored (Kabashima, 1993). There is additional complexity regarding what to include in a product's use phase of the life cycle, especially with green walls as they interact with a building, and the benefits due to reduced energy use for space heating within the building due to increased insulation from the green wall may be difficult to generalise due to the variability of building constructions.

The components involved in all phases of a product's life cycle (manufacture, use, disposal, and transport) need to be considered within an LCA, ranging, in the case of green walls, from energy and water inputs, to the materials supporting the greening system, to the plants themselves (Figure 7.4). Once an inventory has been established (which may vary significantly depending on the size and system used in the installation), data from existing industry sources, LCA databases such as the Green Guide (Anderson and Shiers, 2009), and experimental literature (Hunt and Franklin, 1974, Yeager et al., 1993, Russo and De Lucia Zeller, 2008, Beccaro et al., 2014, Lazzerini et al., 2016) could be used to establish component environmental impacts.

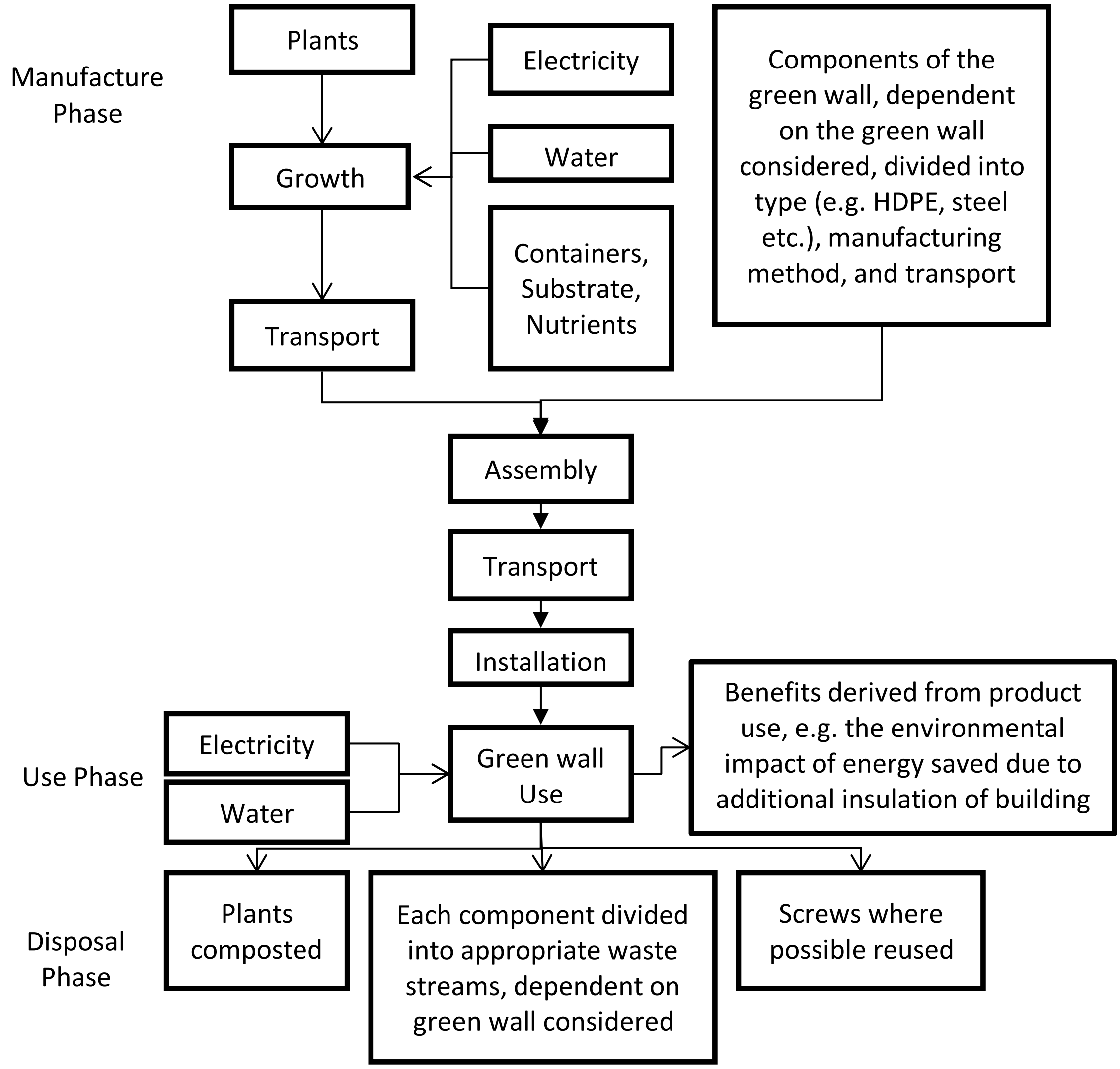

Figure 7.4 Components of a life cycle assessment that would be considered in an LCA of green walls. The plants section would include a basic impact value for the plants' form (such as seeds, plugs or potted) and transport to the nursery. Growth is the first component of the green wall LCA where the inputs would be considered, which would include the growing substrate for the plants such as peat, coconut fibre etc., containers used, and nutrients. The green wall use phase includes inputs required during the lifetime of the green wall and the environmental impact of its use, i.e. for a living wall the inputs are electricity and water, and the beneficial environmental impacts include reduced energy use for space heating due to additional insulation.

The level of confidence that could be placed in this data depends both on the components and life cycle phase under examination. It may be comparatively simple, for example, to account for the impacts resulting from materials used in the manufacture phase as the processes involved have occurred relatively recently and are often subject to regulation (Hunt and Franklin, 1974, Chapman, 1975, Alexander and Greber, 1991). Another example might be the fertiliser and water inputs used to generate and maintain green wall plants, which are predictable to some degree, depending on local climatic conditions (Ottelé et al., 2011, Chambers, 2018).

Other components may present more difficulty. For example, while it is possible to account for transport vehicle emissions in terms of average exhaust content and volume per kilometre, a lot depends on the vehicle's maintenance, the style of driving, and the roads travelled (Bingham et al., 2012, Gallus et al., 2017). Furthermore, it is arguably only possible to account for impacts occurring during the manufacture and earlier parts of the use phases. This is because the impacts and occurrence of events such as developments in technology, alterations to regulations, and changes in ownership cannot be easily taken into account. This would be particularly true during the disposal phase (Nicholson et al., 2009) which may occur decades after installation, a common assessment period or service life for buildings is 60 years (Mundy, 2015), during which time much may have changed. Several green walls in the UK are, however, reaching a stage where components such as drip lines for irrigation may need replacing (Ottelé et al., 2011) including those installed before 2011, such as Edgware Road and Westfield (ANS Global and Chambers, 2018a, Biotecture Ltd., 2018).

Some LCAs of various scopes (ranging from whole life cycle environmental impacts to potential energy savings alone) have been performed for green walls, focussing both on direct and indirect greening (Ottelé et al., 2011, Feng and Hewage, 2014b, Natarajan et al., 2015, Pan and Chu, 2016). Several points arising from these studies are discussed below.

In the case of direct greening, the only materials required are the plants, therefore any environmental impact occurring during the 'manufacture' phase of their life cycle should be minimal compared to no greening at all. Hence, any reduction in environmental impacts occurring during the 'use' phase of direct greening installations (such as cooling, thermal insulation, or temperature stabilisation) should be beneficial overall (Ottelé et al., 2011). The same balance of costs and benefits could not be expected to occur for indirect greening as their material requirements can be much greater, especially in the case of living walls.

The materials utilised in indirect greening (such as trellises, modular units for living walls, and support structures) are, indeed, highly relevant; for example, in temperate climates such as the UK the environmental benefits from indirect greening only outweigh their environmental costs if HDPE (high density polyethylene) is used a support trellis for climbing plants rather than steel (Ottelé et al., 2011). Additionally, geotextile-based living walls can inflict around five times the environmental burden of a planter-based system, and only provide similar or lower environmental benefits in return (Ottelé et al., 2011, Feng and Hewage, 2014b). Partly this is because geotextile-based systems have a shorter 'life' as the geotextile part of the system requires replacing after 10 years, so the beneficial environmental impacts derived from their use are unable to counter air pollution generated during the manufacture of the product. Whereas the beneficial impacts of trellis and planter-based systems should, during their use phase, at least offset the air pollution generated during their manufacture (Feng and Hewage, 2014b). Much of this poor performance can, however, be credited to the current inability of the materials to be recycled, therefore with further innovation, geotextile-based green walls could become sustainable in the future.

In a simulation of a planter-based living wall, when the external layer of masonry was excluded (which could be possible if a living wall was integrated during the construction phase), a further saving to the environmental burden occurred (Ottelé et al., 2011). These additional life cycle cost savings derived from reducing construction materials meant that benefits occurring during the use phase of this living wall came much closer to mitigating the life cycle costs of manufacture and disposal (Ottelé et al., 2011). That calculation only worked for a Mediterranean environment (due to energy savings from cooling the building); however, for a planter based system to be sustainable in the UK, not only would the living wall need to be integrated into the building construction but the system would also be required to impose a smaller environmental burden overall. The green wall on 52 Minories, Tower Bridge, (installed by Biotecture) has avoided the need for a rain screen on the building's outer layer (Dover, 2015) and may provide a good LCA case study for measuring equivalent savings in the UK.

The LCA study by Ottelé (2011) has shown that direct and indirect greening (with *Hedera* or other climbers using HDPE trellis if required), are environmentally sustainable in the UK. However, the LCA calculations did not appear to account for environmental benefits to the surrounding area such as cleaner air, noise reduction, reduced surface water flow, carbon storage and increased biodiversity, so the overall outcome may be more positive than has been previously suggested. Furthermore, new technology often performs poorly in LCAs; given time to develop approaches and economies of scale it may be the case that further types of living wall system could prove sustainable.

7.3.2 Limitations of LCAs

The main limitations of LCAs concerning green walls to date have been the quality of data inputs, a lack of accepted standards, and poor communication of results. The data, assumptions, and scope employed are known to cause significant variation in the outputs of LCAs, specifically by altering the environmental impact rankings of products and services considered (Ayres, 1995, Owens, 1997, Reap et al., 2008a). When considered alongside further assumptions involved in the models and un-validated simulations used to generate environmental 'benefits' (Ottelé et al., 2011), the results of any LCA seem increasingly unreliable (Reap et al., 2008b).

The LCA rankings can, by definition, only be as accurate as the data sets from which the environmental impacts of product components are drawn (Ayres, 1995). Multiple data sets often rank the environmental impacts of components differently (Finnveden and Ekvall, 1998). Two otherwise identical LCAs using variant data sets are, therefore, likely to not only rank the same products differently in terms of their overall impacts but also identify different components as the primary causes of those impacts. This is not conducive to the identification of low impact products and services, or to the targeting of particularly impactful components for improvement. It may also provide an opportunity to manipulate the apparent sustainability of a product without altering life cycle procedures.

A lack of accepted standards, furthermore, means that LCAs are rarely comparable due to variation in their scopes and parameters, for examples that are comparable see and Ottelé et al. (2011), Feng and Hewage (2014b). This may take the form of different assumed lifetimes (20-60 years; (Anderson and Shiers, 2009, Ottelé et al., 2011, Natarajan et al., 2015)) which may have a significant impact on the calculated values for both the detrimental effects of material disposal and the benefits gained from such things as reductions in energy expenditure for cooling. Some assumptions also may not reflect reality, resulting in further confusion. To take an example of this problem occurring at the modelling stage, a study (Natarajan et al., 2015) appears to have used a 1 m^2 functional unit as representative of an entire wall, rather than as part of a larger wall. This skewed the LCA outputs so that the use phase had the greatest environmental impact, whereas most other models found manufacturing to be an area of greater concern (Ottelé et al., 2011, Pan and Chu, 2016).

Differences between what is included in the LCA and the resulting discrepancies between studies suggests that it would be advisable to develop a comprehensive standard methodology for assessing structural greening products (Tedesco et al., 2016, Giordano et al., 2017), including variables such as water use, irrigation method and variation in construction procedures. This standard methodology should include a comprehensive set of calculation methods and a standardised data set to be followed by all green wall installation companies. If such a standard were to be adopted by living wall installation companies, it would become possible to apply a sustainability 'grade' to any structural greening. It is hoped that this would both apply a market force for the creation of more sustainable walls and allow customers to make better informed decisions.

The first step in developing such a standard would be to produce an appropriate set of parameters specific to green walls based on pre-existing or experimentally acquired data. This would cover areas such as an inventory dataset, from which all the standardised LCA would calculate their manufacture, use and end-of-life inputs. Additionally, a building style/type could be modelled to determine whether the presence of a living wall system (LWS) reduces energy use (by cooling/ insulating the building envelope). As there are many different architectural styles used within British building stock (Bruhns, 2008) simulations could be conducted on several model buildings using software such as IES (Integrated Environmental Solutions).

Having reviewed the 215 case studies discussed in section 7.2, buildings occupied by Marks and Spencer Group plc. would be a good candidate for a retail model as they have greened at least eight stores (Figure 7.5). Other possibilities might include supermarket chains, which often utilise company specific building aesthetics as part of their corporate branding (Kirby and Kent, 2010), though none have as yet adopted widespread green wall installations (personal comment).

Figure 7.5 Marks and Spencer store, Newcastle, photograph from ANS Global case studies

The stock for office buildings is very architecturally varied, with almost half built pre-1970 (Bruhns, 2008), though this older category appears to have received no attention in case studies to date. It is therefore difficult to choose an exemplar for modelling purposes; it may be necessary to model on a case by case basis, comparing the potential impact of any new greened structure with the architecturally nearest previous example. Starting points might include Grosvenor House in Luton (a 1980s building retrofit Figure 7.6a) and an office in Webber Street (a modern design Figure 7.6b).

Figure 7.6 L-R: Grosvenor House, Luton (a), office in Webber Street, London (b)
Photographs from Biotecture and Scotscape case studies respectively

For residential properties it might be possible to derive a model from the Parker Morris standards applied to housing stock developed between 1967 and 1980 (Park, 2015). This assumes that residential developments of this era are representative of British housing stock (Hamilton et al., 2013) and that the Parker Morris standards have continued to shape modern residential construction, the latter of which is possible but hard to prove. Even if this were the case, it might be necessary to produce separate models accounting for variation in insulation efficiency.

The objective of generating a standard would be to reach a point where LWS generally use less energy and generate less pollution during their manufacture phase than they will offset through energy savings, pollutant and particulate capture over a lifetime of use. Once this aim has been achieved per meter squared of greened building it could then act as a form of certification for green wall companies and installations. It is hoped that doing so would drive further advances in sustainability and act to advertise the benefits of green walls to a wider audience.

7.4 Barriers to green wall installation

Barriers to green façade installation are minimal when compared to LWS, but tend to revolve around building damage, nuisance to residents caused by insects, reduced light availability, and the costs of maintenance (Köhler, 2008). In the UK there are also public concerns, exacerbated by popular media (BRE et al., 1996, Cannell, 1998, Howell, 2003, Watt, 2009, Douglas & Noy, 2011), surrounding the tendency of direct greening to damage structures and increase their vulnerability to damp. This is despite an established body of evidence that ivy and other climbers are suitable for structurally sound walls, and those not constructed using lime mortar (Sternberg et al., 2010a, Viles et al., 2011). Barriers to indirect greening are more likely to be cost-based due to the requirement for additional structural elements including high tension steel wires, timber trellis, planters/modules and irrigation/nutrients depending on the technique considered. There are still some issues regarding maintenance and pruning, but these are balanced by a lower incidence of damp, damage, and gutter blockage.

The barriers to LWS installation are likely to be similar to the barriers to the adoption of any new technology (Peck et al., 1999, Bradley et al., 2016). These barriers involve cost, limited knowledge, uncertainty of the benefits, concern regarding the disruption to the lived environment, social implications of the innovation, and other budgetary priorities (Peck et al., 1999, Rogers, 2000). Living walls also have extensive maintenance requirements, which if ignored can lead to a prominent and costly problem (Lombardi et al., 2012).

There are four elements required to increase the uptake of a new sustainable technology such as green roofs or green walls: a vision, stakeholder participation, policy, and funding (Peck et al., 1999). Similarly, a Natural England report (2013b) states that to motivate GI installations, including green walls, four processes were required: audits (to check what already exists and where the potential is), strategy or planning (how to protect and enhance current assets and where to develop new assets), funding streams, and finally delivering or installing the GI (Natural England, 2013b). The vision surrounding structural greening is well established (Köhler, 2008, GLA, 2009, 2011, 2017a Perini et al., 2011b, Hunter et al., 2014), several funding streams have been created (Victoria BID, 2014, Cinderby et al., 2015, Groundwork London and Hammersmith & Fulham Council, 2016), and many audits performed (Victoria BID, 2013, Thomas, 2015, Deen et al., 2016, Nolan, 2017), but widespread stakeholder buy-in remains elusive. The reasons for this are likely complex but largely revolve around the generally unfavourable performance of green walls in a common decision-support tool, cost-benefit analysis; CBA (Hwang, 2016). The following sections will examine the nature of CBA, its flaws, and methods for restoring the cost-benefit balance.

7.4.1 Cost-benefit analysis

Another method of assessing the sustainability of structural greening is CBA. A CBA is a rapid, simple method of assessing the overall viability of any decision (Hwang, 2016) and can be used to account for intangible benefits and costs as well as financial ones.

There are several known problems with using a CBA for environmental assessments, such as that the costs and benefits included within the same model are not directly comparable (costs are typically directly measurable in financial terms but benefits are often intangible, and therefore approximated via increasingly inscrutable methods; Ashford, 1981, Ackerman, 2008). Additionally, CBA is subject to many of the same assumptions and scoping issues as LCAs (see section 7.3.2), and outputs are only as good as the input data. This makes CBAs situational and specific; not a generalised tool.

As CBAs are largely tools for judging the economic, rather than environmental sustainability of any decision, they are useful to support decision-making but other factors such as maintaining equity and an awareness of morally dubious but economically logical options are also required to make holistic choices (Ashford, 1981, Ackerman, 2008). Including these factors, however, adds further layers of complication and value judgements, so despite its limitations, like the LCA a CBA may be a useful starting point, from which over time; further assessments may be conducted. It will, therefore, be necessary to seek ways in which the benefits of green walls can be expressed financially and these benefits advertised to stakeholders.

7.4.1.1 Monetising the benefits of green walls

A cost-benefit analysis of green walls by Perini and Rosasco (2013) showed that over 50 years in a Mediterranean climate (where the cost savings from reduced energy use for cooling are greater), only direct green façades (such as *Hedera* cladding) were economically sustainable in all analysed scenarios. Supported climbing plants, however, as with the LCA, were only financially viable with HDPE trellises, and living wall systems (LWS) were not economically sustainable under any scenario. Direct green façades had an average 20-year payback period (after which the benefits outweigh the costs of installation; (Perini and Rosasco, 2013)). In Hong Kong, the payback period of a planter-based system was 40 years, based on air conditioning energy savings alone (Pan and Chu, 2016), which shows that depending on the climate, some LWS can be economically viable, especially if other benefits (such as increased property prices in greened areas) are taken into account. In a temperate climate like the UK, however, no current CBAs appear to show that LWS are economically viable. Therefore the following section will investigate whether LWS could become economically viable if more benefits were monetised and factored into the calculations, or with the provision of government incentives or additional funding sources.

7.4.1.2 Potential methods for monetising the benefits of green walls based on lessons from other forms of green infrastructure

The economic value of green infrastructure (GI) and GI investment in the UK has been increasingly well understood since a report commissioned in 2004 by Natural Economy Northwest reviewed the economic benefits of GI (ECOTEC Research and Consulting, 2008). This report applied 11 criteria to assess the economic value of GI, of which the most relevant to green walls included land and property values, economic growth and investment, land and biodiversity, and quality of place.

While the presence of greenery (including trees and parks) has been found to increase property prices by 5-15% (Natural England, 2009), an additional benefit (potentially financial) may come from a reduction in airborne particulate pollutants (Chay and Greenstone, 2005), as may result from green walls (Sternberg et al., 2010b, Perini et al., 2017b, Weerakkody et al., 2017). For example, in the USA; counties whose air quality did not meet the minimum acceptable standard observed a 2.5% increase in property prices when atmospheric pollutant particulates were reduced by 10 μgm^{-3} (Chay and Greenstone, 2005), whether this effect would be additive to the observed increase in property prices due to greenery has not been researched. Explicit evaluation and advertisement of this dual benefit (increased property values and cleaner air) may induce the wider adoption of green walls in the residential sector. There may also be a notable confusion of cause and effect where it appears that green cities attract highly educated residents and the accompanying economic benefits (Kahn, 2006, Natural Economy Northwest, 2010). It may, however, be that given greener areas/neighbourhoods tend to be more expensive (ECOTEC Research and Consulting, 2008) and educated people tend to be more affluent (Condron, 2013), the presence of educated people in green areas is due to their ability to afford more expensive properties.

An additional method to monetise benefits may be to perform a social return on investment (SROI), which is a method of accounting for the social, environmental, and economic costs and benefits of a project. For example, an SROI conducted on a wide range of blue and green infrastructure changes made to a housing estate in London (to demonstrate GI uses in climate proofing social housing) found that the full range of changes and volunteer involvement used to implement them gave an SROI of £4.39 (with a range of £2.31-5.15 from the sensitivity analysis) for every £1 invested (Groundwork London and Hammersmith & Fulham Council, 2016). Unfortunately this analysis did not look into the effect of individual changes, nor did it account for greening specific benefits such as a reduced urban heat island effect for the estate, increased biodiversity, air pollution reduction, and the potential increase in property values.

Furthermore in the commercial realm, case studies have shown that achieving an award and developing premises that support biodiversity increases customer satisfaction, encouraged repeat custom, and helped generate new customers (Natural Economy Northwest, 2009). Additionally, staff morale was boosted, leading to a better working environment, therefore increasing staff productivity and reducing turnover. Aesthetically pleasing plantings such as hedgerows and *Hedera* screens/cladding may also prove cheaper than conventional boundary markers (Natural Economy Northwest, 2009). Unfortunately the pilot report did not give a breakdown as to how many of these case studies reported which findings, or an approximate CBA of the biodiversity initiatives.

Some potentially monetisable benefits of green walls apply equally to residential and commercial properties, including increased respiratory health. The atmospheric pollutant capture abilities of vegetation, especially *Hedera*, are well established (Chapter 1 section 1.2.4, Ottelé et al., 2010, Sternberg et al., 2010b, Grundström and Pleijel, 2014, Perini et al., 2017b, Weerakkody et al., 2017) as are the interlinked health effects of exposure to nitrous oxides (NO_x) and particulates including damage to lung tissue, decreased lung function, and shortened lifespan (WHO, 2013, EPA, 2018). The effects of NO_x have, however, been monetised more frequently than those of particulates, creating some difficulty in judging the financial benefits per tonne of particulate removal by GI. A report by Defra (2015) shows that the cost per tonne of NO_x and particulate emissions for all urban transport sources, particularly in London, are higher than the health costs associated with either domestic, waste or industrial sources of NO_x and particulates. Therefore, even expensive pollutant removal methods may remain cost effective in the capital, where the average cost to health was calculated to be between £64,605 and £96,171 per tonne of NO_2. However, while this provides a useful starting point for green wall monetisation, health cost calculations do not take into account the further benefits of removing NO_x from the atmosphere, such as reductions in EU-imposed fines. As discussed above, the primary monetisable benefit of green walls is their ability to capture pollutants, especially due to their position in 'street canyons' (see Chapter 1 section 1.2.4).

7.4.2 Funding streams for UK green walls

Green walls contribute a wide range of benefits which (as discussed in section 7.4.1.2) can be increasingly monetised and, when a wider view of economics is considered (including social and environmental benefits) have the potential to be cost effective (when using CBA). However, to overcome the considerable capital costs involved in green wall installations, financial incentives are still beneficial.

Case studies and targeted web searches (see section 7.2) reveal that green walls across the UK are funded in numerous ways, from self-funding by private individuals (in the case of residential installations), through to complex mixtures of trusts, sponsors, and grants provided by charities, co-operative business organisations (namely business improvement districts; BIDs), or government bodies (such as Transport for London). Additionally, it can become challenging to discover who funded projects, especially when there are multiple partners acting together. Corporate bodies e.g. Volkswagen, Porsche and Marks and Spencer (ANS Global and Chambers, 2018a, Scotscape, 2018) may also fund their own green walls for visual impact and branding purposes or in the case of Marks and Spencer, as an advertisement of the company's commitment to sustainability (M&S, 2017).

Given the complex diversity of funding streams available for the installation of green walls on public and commercial buildings these will be dealt with first.

In 2009, the then Mayor of London (Boris Johnson), set out a vision for at least a 5% increase by 2030 and a further 5% increase in green infrastructure in London, including green walls, by 2050 (GLA, 2009). The targets were translated into policies 5.10 and 5.11 in the London Plan 2011, though these were only applied to the central activities zone (CAZ) within inner London (GLA, 2011). The current Mayor of London, Sadiq Khan, has continued this vision with the aim of turning London into the first 'National park city' by 2019 and greening 50% of London by 2050 though this document is currently in draft form (GLA, 2017a). As a result of these visions, funding streams have been developed and partnerships such as the Cross River Partnership have been working with BIDs to achieve those goals. These include examples of top-down funding streams, which are frequently provided, directly or indirectly by the EU, such as the European regional development fund (ERDF), Life++, and Horizon 2020 (European Commission, 2018) and encouraged the creation of bottom-up funding streams such as BIDs.

Business improvement districts (BIDs) are collectives of businesses, operating within a narrow zone, and working together to pool resources and improve their area through measures such as GI, street cleaning, and crime prevention (Victoria BID, 2014); the first BIDs appear to date back to 1960's Michigan, USA; Public Act 120, 1961 Michigan (State of Michigan Legislative Council, 2017). The benefits to business owners of being part of a BID are potentially greater footfall, customers staying for longer, and increased spending. The business owners vote to establish/remain part of the BID, and pay a levy which is applied to businesses over a certain threshold (based on the rateable value of their property) and a voluntary fund from landowners (Victoria BID, 2014). There are currently 291 BIDS in the UK and ROI of which 241 are in towns and cities (BritishBIDs, 2018). Several BIDS, especially in London, have provided a way of financing GI projects using the collected levy to match available funding streams. The money raised by BIDs can fund a wide range of schemes including more expensive and exploratory projects such as rain gardens and living walls, as well as cheaper green roofs and greened façades (Cinderby et al., 2015).

As part of the BIDs activities audits of sites for potential green infrastructure have been undertaken, alongside audits looking at existing GI installations with a view to recognising their value and proposing improvements. In order to aid these activities an auditing guide has been produced (Victoria BID, 2013) and methods to assess the economic value of established and proposed GI have been developed in the form of various valuation tools (Green Infrastructure North West, 2011, Natural England, 2013a). As a result there have been increasing numbers of GI audits generated by local authorities, BIDs and District Councils. This has allowed for new and enhanced GI opportunities to be explored from which a business plan can be developed and put to stakeholders (Nolan, 2017).

To achieve the Mayor of London's target to increase green cover in the CAZ by 5%, an initiative was set up called 'Greening the BIDs' to work together with the Cross River Partnership (Thomas, 2015). This is a group of several BIDS within the CAZ formed to coordinate regeneration efforts and to take advantage of related government initiatives (CRP, 2016, 2018). As part of the 'Greening the BIDs' initiative, five million square metres of the CAZ has been audited and potential sites for over 200 green walls have been identified (Thomas, 2015), along with over 4,100 m^2 of green walls both extensive (direct and indirect greening) and intensive (LWS; Kimpton et al. (2012), The Ecology Consultancy and The Green Roof Consultancy (2012)). As a result of these audits, the BIDs were then involved in organising at least nine green wall installations in the CAZ, with the aim of improving the district for all businesses and residents involved. The newly created green walls were funded through BID levies, and sometimes additional grants collected through either BID initiatives or by overarching partnerships e.g. Cross River Partnership. An example of a green wall funded by such arrangements has been applied to the Rubens Palace Hotel, which supports a 350-450 m^2 living wall irrigated with rainwater, intended to reduce flooding, and improve building insulation (Cinderby et al., 2015). Some green infrastructure was also paid for in part or wholly by the company that benefitted most from its installation e.g. the John Lewis rain garden in the Victoria BID (Cinderby et al., 2015).

There are also a number of grants and funding schemes (such as lottery funding, the 'green capital and community green space' grants, or Mayoral grants/funds for example, the 'clean air fund') that could be accessed to improve GI. In London, as part of the Mayors 'greening the capital' movements (both Boris Johnson and Sadiq Khan), a large amount of 1:1 funding (where the Greater London Authority matches sums already raised for GI installation) has been made available to incentivise demonstration and wider greening projects. While it is challenging to determine the impact of multiple approach initiatives such as the Mayor's air quality fund (which also provided investments for education, tree planting, and electric vehicles) this, along with other greening measures, is calculated to have resulted in at least 1,012 m^2 of green wall installations (GLA, 2016). To access these funds, however, many bodies (including BIDs and district councils) may need specialist help in constructing suitable funding requests; this has previously been provided by partnerships with NGOs (such as Groundwork) and other trusts. To the best of our knowledge, there are no funding streams for structural greening currently available to private homeowners in UK, which is an oversight as there are more residential properties than commercial or government owned buildings.

Additional funding streams available to local authorities and BIDs for GI development include the community infrastructure levies (CILs) established by the CILs Regulations 2010. Within a CIL charging zone (as demarcated by local authorities), a levy is applied to new non-residential developments (over 100 m^2 internal floor space), and any residential developments where applicable (The Stationery Office, 2010a). Money raised by these levies can be invested in GI both around the development and within the neighbourhood as a whole (Landscape Institute, 2013). There are, however, no existing records of the quantity or quality of GI produced as a result of CILs.

The power of BIDs to implement and maintain GI is increasingly recognised in reports such as the 'All London Green Grid' supplementary planning guidance (GLA, 2012, Merk et al., 2012). This, along with the number of BID sponsored green wall installations constructed in London since 2009, suggests that the best method of funding structural greening, and GI in general, is a combination of top-down (publicly sponsored), and bottom-up (stakeholder led), solutions. A similar mixture of large and small scale approaches can be seen in the planning and policies surrounding green walls (Department for Communities and Local Government, 2012, Westminster City Council, 2016b, The National Archives, 2018).

7.5 Planning and policy for GI in the UK

London has been chosen as a case study as it has more green walls than any other part of the UK and is governed by multiple complex layers of public bodies; therefore if GI can be implemented within the London planning system, the appropriate layers could then be modelled for most other situations in the UK. There are 32 borough councils and the City of London Corporation inside the boundaries of Greater London; each of the boroughs run the land within their boundaries, though the City of London Corporation also controls some green spaces outside of the Square Mile (the domain of the City of London e.g. Epping Forest and Hampstead Heath (City of London, 2018)). Overarching the London boroughs is the Greater London Authority (GLA), headed by the Mayor of London, which produces policies for the whole region (excluding the City of London proper).

British planning policy is based on a complex mixture of statutory and non-statutory policies, and at each level there are points directly encouraging the provision or maintenance of GI. Area specific guidance for borough plans within each of the 32 London boroughs is derived from supplementary planning guidance and the overarching London Plan (Figure 7.7).

There are many opportunities for 'top-down' policies from the National Planning Framework and 'bottom-up' drivers from neighbourhood groups and BIDS to interact within the development process of a 'Local Plan'. This can be seen by multiple statements in BID and local government action plans offering GI aims and visions. For example, one stated aim within the Baker Street BID action plan was to "Make Baker Street Quarter the greenest neighbourhood in central London" (Aretis et al., 2015); simultaneously the London borough of Westminster (within which the Baker street BID lies), has developed a separate low emission neighbourhood (LEN) strategy (the Marylebone LEN) encouraging GI (Westminster City Council, 2016a). Furthermore, the London Borough of Westminster is part of the All London Green Grid (ALGG) which is a cross-borough GI planning initiative intended to encourage the development of green corridors (GLA, 2012). As a result of these interacting planning systems a further four green walls than initially planned by the BID and LEN separately were proposed within the area covered by both (Aretis et al., 2015, Westminster City Council, 2016a). This example highlights not only the complexity of the policies, especially in London, but also the opportunities for increasing drivers for the development of green wall installations. Where one area misses an opportunity, another may drive its installation.

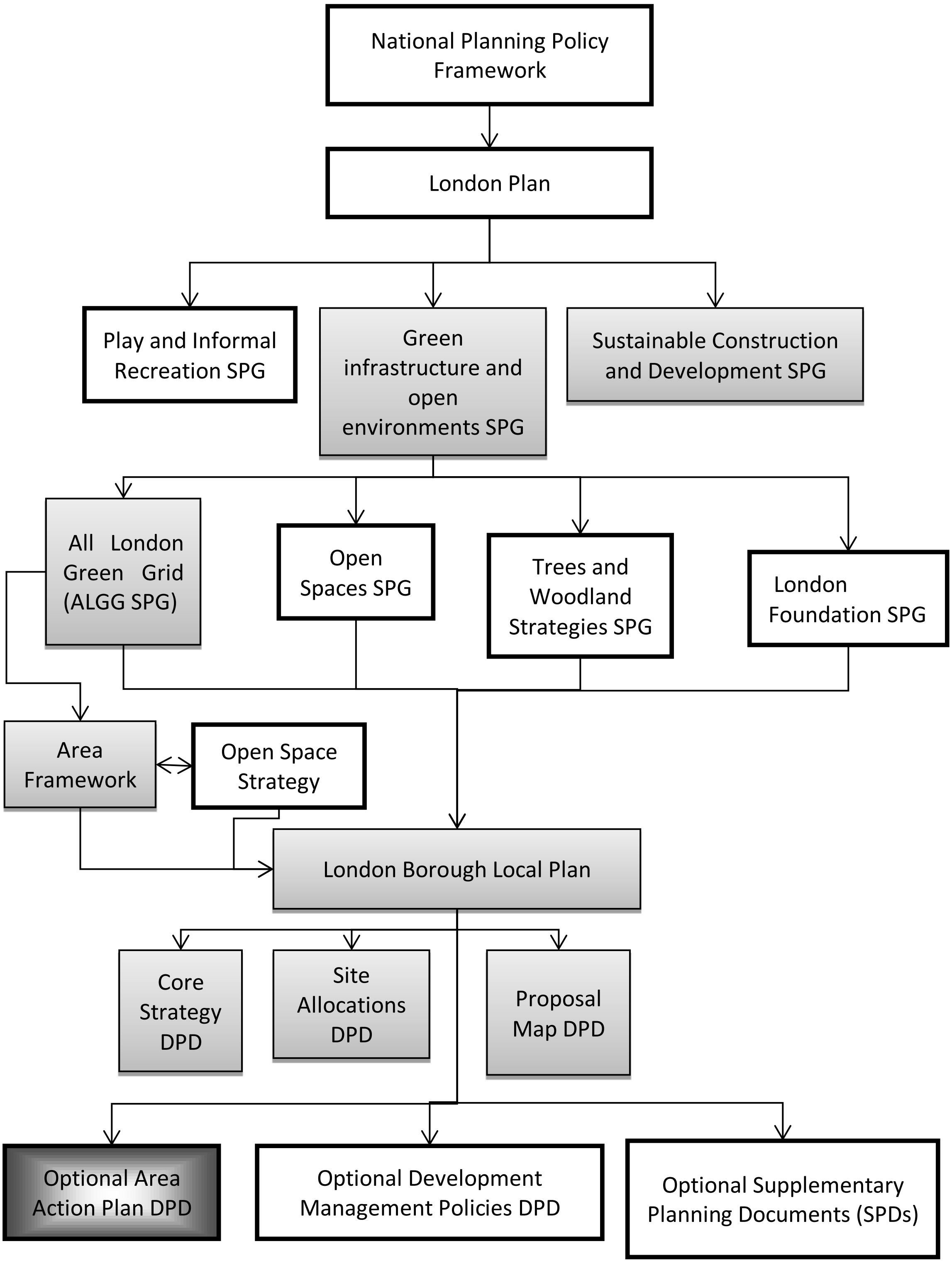

Figure 7.7 Planning policy framework for London, based on an updated chart summarised from GLA (2011), GLA (2012), and Westminster City Council (2016b). An SPG is supplementary planning guidance, a DPD is a Development Plan Document and SPDs are Supplementary Planning Documents. The policies and guidance from each level in the framework guide and drive the policies in the next level of the framework. The grey boxes have policy or guidance relating to green infrastructure and green walls in particular.

This multi-levelled approach means there are many opportunities for interested parties to influence planning policies surrounding GI. One such potential group are the community development trusts (CDTs), which are developed to improve communities and respond to local needs. As such, CDTs use partnerships to access funding which can then be used to further their cause (Wilcox, 1998). These causes can include environmental redevelopment, and therefore CDTs could be used to support local GI, however, while CDTs can include GI elements, they do not seem to be as central to CDTs as BIDs. Given that there are currently 500 development trusts in the UK (DTA Wales, 2018); CDTs may become a significant resource for campaigning if they are made aware of GI benefits.

7.5.1 Green Space Factor and green points schemes

One method of adding minimum requirements for GI to planning permission has been the green space factor (GSF). This was first developed in Berlin, Germany, and tested in West Berlin during the 1980s, where it is called the Biotop Flächenfaktor or biotope area factor; BAF (Landschaft Planen & Bauen and Richard, 1990, Dover, 2015). The scheme stopped when the Berlin wall came down but was restarted in 1994 and is still in place currently (Senatsverwaltung für Umwelt Verkehr und Klimaschutz, 2018). In the New London Plan, the Mayor of London has suggested introducing a similar urban greening factor (UGF) requirement for all new developments, with each borough developing plans for its incorporation (GLA, 2017b). Several other planning authorities including Northwest Regional Development Agency (Community Forests Northwest, 2011), and Southampton City Council (Southampton City Council, 2015) have also been trialling various forms of GSF.

The green space factor is an incremental system of points between 0 and 1, which are assigned to different forms of 'green activity' such as green walls or trees. The area covered by the green activity, e.g. a green wall, is multiplied by the value assigned to that activity; this figure is then divided by the total area of land to be developed (Equation [7.1]).

$$\frac{\sum(Area\ of\ green\ activity * value\ assigned\ to\ that\ activity)}{Total\ development\ area} = Green\ Space\ Factor\ (GSF) \tag{7.1}$$

The GSF calculated for each green activity is summed, and a value between 0 and 1 is assigned to the development as a whole. It is possible, though rare to get a value greater than 1 when green walls are included, as this means there is more greened area than possible from the building footprint alone, due to the inclusion of vertical surfaces. The minimum requirements in Germany, UK, USA, Sweden, and Finland for planning permission are typically between 0.3 and 0.6, depending on area use; around 0.3 for commercial zones and 0.6 for residential zones (Landschaft Planen & Bauen and Richard, 1990, Järvelä and Tiihonen, 2014, LaClergue, ca. 2014, Dover, 2015, GLA, 2017b).

GSF schemes have been implemented in Malmö, Sweden (2001); Seattle, USA (installed 2006, expanded in 2009); Helsinki, Finland (2012-2014); Washington DC, USA (2013); and in 2015 in Southampton, UK (ASLA, 2010, District of Columbia Municipal Regulations and District of Columbia Register, 2013, Järvelä and Tiihonen, 2014, Dover, 2015, Harris, 2015). The city of Malmö has added another layer to the system with green points; developments must achieve the minimum GSF requirement plus 10 Green Points, which are specific biodiversity objectives e.g. walls covered in climbing plants (Kruuse, 2011).

The benefit of the green points system is that planning authorities can tailor the scheme to improve GI quality according to the ecological requirements of the area. For example, if an area hosted enclaves of declining species (such as hedgehogs or small tortoiseshell butterflies), the points system could require developments to include measures supporting these species in order to gain planning permission. Additionally, it may be possible to encourage the planting of species that support the requirements of insects in decline locally or nationally, as long as the plants involved could grow sufficiently well under local conditions.

There were some concerns that the UGF suggested by the Mayor of London may turn into a 'tick box' exercise, with developments choosing the cheapest options to get the most space value (Grant et al., 2017). The inclusion of a green points system in the London UGF could, however, allay those concerns by adding quality to the quantity element of the GSF (Dover, 2015).

7.6 Methods for increasing green wall uptake

As the technology for green roofs has been developed for longer than green walls and their adoption has become increasingly mainstream, especially in countries like Germany, there is a greater body of evidence for the incentivisation and encouragement of green roof installations; hence these will be used as inspiration for methods that may support green wall uptake. Green roof uptake has been increased in multiple ways, however, they tend to fall into four categories: regulations, subsidies, education, and technical assistance (Ansel and Appl, 2014), of which the primary focus of this section will be regulation and direct financial incentivisation, as these tend to produce the greatest impact.

7.6.1 Regulations

Regulations can be mandatory or non-mandatory as well as statutory or non-statutory (either encoded in law or created to increase compliance with an existing law). Examples of statutory regulations could include changes to the building code (if they were made) or the by-law in Sheffield (Dover, 2015) which mandates the installation of green roofs on new developments over a certain size. Statutory regulations stipulating green roof installation have been passed in Malmö, Sweden; Copenhagen, Denmark; 28 cities in Germany including Berlin and Stuttgart; Basel and Zurich, Switzerland; Recife, Brazil; Cordoba, Argentina; Toronto, Canada; and Portland, USA (Ngan, 2004, EcoMetrix Solutions Group LLC, 2014, Dover, 2015, Progrss, 2016, Lemos and Kauškale, 2017). Additionally, Japan is one of the few places where such regulations have been applied across the whole country (Ngan, 2004). Mandatory statutory regulations, while likely to be very successful once passed (depending on the extent to which they are enforced), may be highly controversial during their drawing up stages, due to for example, resistance to change and fears of resultant costs. This may result in the legislation being set aside, delayed indefinitely, or extensively diluted (Hall, 2010, Hampton, 2014).

Furthermore, a framework of technical and industry standards is required to avoid errors in installation ranging from leaks to structural collapse, which can reduce confidence in the industry and therefore uptake for several years (Ngan, 2004, Kuo, 2016).

Types of legislation likely to create less controversy are mandatory regulations where multiple greening options can be chosen without stipulating the requirement of a green roof; 35 German cities include green roofs as an option to mitigate nature losses during construction (Ngan, 2004). Greening factors may also be included within this category (Dover, 2015, Grant et al., 2017). This form of regulation has less impact on green roof/wall uptake, but may be more acceptable than single choice mandatory regulations as it allows developers some freedom to adapt their strategy to site conditions and planned development specifications (Ngan, 2004).

Non-statutory regulations, such as the ‘All London Green Grid’ and the ‘Greening the BIDs’, encourage greening without stipulating requirements, and have encountered significant success in the UK (GLA, 2012, CRP, 2016). These regulations highlight the importance and benefits of GI and may suggest multiple options for suitable installations, such as street trees, planter boxes, and green walls (GLA, 2012, CRP, 2016). Non-statutory regulations have so far encouraged 300,000 m^2 of green roofs in London (Townshend and Duggie, 2007), suggesting that they might represent the best solution for greening British urban environments, though, due to their legally non-binding nature there will be no guaranteed impact on green roof or wall uptake.

As matters currently stand in the UK, the 1990 Town and Country Planning Act (The Stationery Office, 1990) enables local governing bodies to set planning obligations of limited scope under section 106, allowing for a combination of statutory and non-statutory regulations to be brought into existence across the country. These can be used to enforce the inclusion of GI (such as green walls/roofs, and tree planting) in order to mitigate the adverse environmental effects of a development. Despite over 25 years of use, however, a report by Natural England acknowledged that the extent and quality of GI secured through section 106 agreements was still unknown as it was very rarely inspected (Natural England, 2015).

7.6.2 Incentives

The impact of an incentive on the uptake of any 'good' (such as green roofs; GR), depends on whether the incentive (e.g. subsidy) mitigates any gaps in the economic cost-benefit analysis, or increases benefits to a point where they exceed those of alternatives (Claus and Rousseau, 2012). There are several ways to do this including direct and indirect financial incentives (such as subsidies and tax rebates/expedited planning permission respectively), and educational initiatives.

Direct financial incentives for GRs, subsidies typically averaging 38 €/m² (values range from 8-50 €/m²), have been offered by many cities in countries across Europe, Asia, and North America (Ngan, 2004, Kazmierczak and Carter, 2010, Greenroofs.com, 2018, Kerssen, 2018). In Portland (USA) the subsidy was at the high end at 53 $/m² (42.27 €/m² at time of writing) (EcoMetrix Solutions Group LLC, 2014), which may reflect high local property prices and the costs of supplying an emerging market. Additionally, the Skyrise Greenery incentive scheme in the Republic of Singapore (which has existed since 2011) finances up to 50% of the installation costs involved in any structural greening project (Irga et al., 2017). Subsidies currently available for GR generally cover up to half the cost of an installation; therefore twice the area forecast at the time of subsidy creation is often greened (Ngan, 2004, Kazmierczak and Carter, 2010, Greenroofs.com, 2018, Kerssen, 2018).

A cost-benefit analysis considering social and environmental aspects should first be conducted to determine the extent to which returns on the investment will cover its costs and hence whether it is worth creating a subsidy (Claus and Rousseau, 2012). If the public benefits outweigh the cost of the subsidy it is probably worth subsidising the activity (Claus and Rousseau, 2012). Subsidies are, however, only likely to support the desired actions for as long as funding is offered; since subsidies for green roof installation in Berlin were discontinued, several planned roof greening projects have been cancelled as, although green roofs qualify for a stormwater tax rebate, that rebate is not sufficient to provide a sustainable return on investment (Nickel 2014). Furthermore, while direct financial incentives are believed to be high impact, the use of subsidies has not been found to reduce the costs of installation by a statistically significant amount over a five year period (EcoMetrix Solutions Group LLC, 2014). This suggests that subsidisation may represent a disincentive to industry efficiency which compounds the requirement for continuous subsidy. There are several ways to avoid this problem, two of which are to create self-sustaining subsidies generated by levies or tax income, or to establish subsidies prior to a mandatory greening requirement, therefore softening its introduction (Ngan, 2004, Townshend and Duggie, 2007).

Indirect financial incentives for GR installation can include tax incentives, such as rebates or reductions in stormwater rates (Dover, 2015), as established by 29 German cities in 2002 (Ngan, 2004), and development benefits, such as expedited planning permission or increases in permissible floor area (floor area ratio (FAR), gross floor area (GFA), and site coverage (SC) -bonuses; collectively termed density benefits (Ansel and Appl, 2014)).

Planning-related indirect financial incentives have been used in Hong Kong (China), where joint practice notes 1 and 2 include density benefits for buildings with communal green roofs (Irga et al., 2017), and Seattle (USA) which gives FAR bonuses to buildings attaining a silver LEED certificate (Leadership in Energy and Environmental Design; an international eco-building scheme), which was frequently achieved with a GR (McIntosh, 2010, Plant Connection Inc., 2018). Additionally, in Chicago (USA) density benefits and expedited (rapid) planning permission were awarded where a GR was included in plans, whereas San Francisco (USA) offered expedited planning as their only indirect incentive (Wood et al., 2014, Greenroofs.com, 2018).

Tax incentives are equally common, found in both Berlin (2000) and Cologne (2001) which charge reduced stormwater fees and provide rebates to the owners of buildings bearing green roofs (Ngan, 2004, Nickel et al., 2014). Additionally, the introduction of a stormwater code in Seattle in 2009 (updated in 2016) allowed the owners of buildings with green roofs to claim a rebate (Irga et al., 2017, City of Seattle, 2018).

Indirect financial incentivisation is likely to be a medium to low impact incentive on its own, but often levying fewer associated costs than direct financial incentives and providing less opportunity for public outcry than mandatory regulations (Ngan, 2004). The level of opposition to proposed stormwater fees (a mandatory regulation, but necessary for any rebate on those fees to become an incentive), can depend their method of introduction and the level of public understanding behind potential tariff structures (Hall, 2010, Hampton, 2014).

Competitions and media coverage to boost knowledge of green roofs and their benefits, such as the CEEweb GR beauty contest and the green roof competition in Australia (CEEweb, 2016, City of Greater Geelong, 2017), create the lowest direct costs but are also unlikely to produce a strong impact. Competitions can, however, increase interest in the area, be used for demonstration projects, and as occurred in Barcelona start an urban greening initiative (Ajuntament de Barcelona, 2013, Ajuntament de Barcelona, 2018). Media coverage and competitions may, furthermore, be used to boost greening uptake if growth in installation is slowing, or if neighbouring areas offer incentives which cannot be implemented locally (Ngan, 2004). Media interest in GI generally, can also increase public awareness of the concept and benefits derived from it, of the existence of direct financial incentives, and of changes in policy (IMAP, 2013). This form of publicity has been successful in increasing awareness of hedges/*Hedera* screens for particulate capture by schools and along roadsides (Bodkin, 2017, Peel, 2017, Finch, 2018, Gaunt, 2018, Hedges Direct, 2018) and typically works best when paired with an enthusiastic leader (Ngan, 2004).

Finally, public relations and education services are an important part of any installation strategy (either publically or commercially led), and should be present from the start of the scheme to help overcome fears and knowledge gaps surrounding the technology (Ansel and Appl, 2014). Local government can encourage technology uptake by greening public buildings (Tam et al., 2011), and backing novel uses such as bike sheds and bus shelters (Dover, 2015). This can, however, represent a risky option for local government as there have been occasions where the public funding of green walls has led to accusations of tax revenue misuse (Fulcher, 2009, Your local Guardian, 2011).

7.6.2.1 Evidence for the impacts of incentivisation

There have, so far, been few studies looking at the extent to which various GR incentivisation methods are effective in encouraging structural greening in either the short or long term. Therefore, while arguments can be made based on logic, it is difficult state the magnitude of uptake for any measure, other than subsidy.

An overview of the incentives used to increase GR installations based on data analysed from 19 case studies of cities across the globe (Ansel, 2018) was summarised in Table 7.1. Incentivisation of GR installations began in Germany and Austria with schemes established in Berlin, Dusseldorf, Karlsruhe, Linz, and Stuttgart from 1979. While many environmental benefits of GR installation were acknowledged in each city, typically one or more of them was the primary driver for the incentive scheme. The top three principal drivers were mitigating the urban heat island effect, improving stormwater management, and increasing biodiversity, though Malmö (Sweden), Amsterdam (Netherlands) and Vienna (Austria) stated the importance of all benefits as drivers. The GR initiative schemes typically contained up to three primary elements, which could be implemented in any order: demonstration projects (to increase confidence in the technology), policy measures (either statutory with compulsory or optional GR or non-statutory to encourage installations), and/or financial subsidies. These practises, in the cities considered, resulted in at least nine million square metres of GR installations (Table 7.1), which is a highly conservative estimate as few of them maintain comprehensive yearly GR installation records.

Table 7.1 A summary of green roof (GR) installation case studies based on 19 cities globally, 5 cities in North America, 11 in Europe, and 3 in Asia; all the case studies had either policy to support GR uptake and/or a direct financial incentive, the first known GR initiative in each country occurred between 1979 and 2008, the case studies were retrieved from Ansel (2018).

Environmental benefits due to GR installation	Number of case studies	Primary expected benefit
Stormwater management	19	7
Biodiversity	19	4
UHIE	18	8
Air quality	13	1
Climate change mitigation	15	2
Energy savings	12	1
City beautification	17	0
Increased living quality	1	0
Generating accessible open spaces	1	1
Reduced transportation emissions from food production	1	0
Incentives used to promote GR installations		
Statutory policy mandatory GR (e.g. land-use plan, GR bylaw, zoning code, design regulations, etc.)	9	
Statutory policy optional GR (e.g. GSF, zoning codes, land-use plans, and design regulations)	12	
Non-statutory policy encouraging GR (ALGG, zoning code, land-use plan, design regulations)	6	
Eco-certification (e.g. LEED) for planning permission	2	
Reduced stormwater fee	6	
Financial Incentives	11	
Tax Credits	1	
Favourable Credit Terms	1	
Density Bonus	6	
Demonstration Projects	15	
Press, Internet	17	
Education and Information (e.g. seminars, conferences, green roof tours, etc.)	15	
Research	9	
Local Green Roof Guidelines	6	
Consultancy offer for constructors, etc.	9	
Other instruments	9	
GR total surface area m^2	9,216,108	

In addition, limited data has been gathered concerning the prevalence of green roof (GR) installation in four urban areas offering various incentives: Portland and Seattle, USA; Flanders, Belgium; and Tokyo, Japan. The following section will compare these datasets with the intention of reaching an evidence based conclusion.

The impact of different incentives on GR uptake varies, and to avoid false conclusions based on the effect of population size, GR area was assessed per thousand residents (Figure 7.8). As data used to investigate the impact of incentives was based on published and open source data, rather than gathered independently, there are some caveats concerning comparisons between these cities. Both the data for Flanders and that for Portland are likely to under-represent the area of green roofs installed, as the data collected from Flanders represents only subsidised installations and from Portland only extensive green roofs.

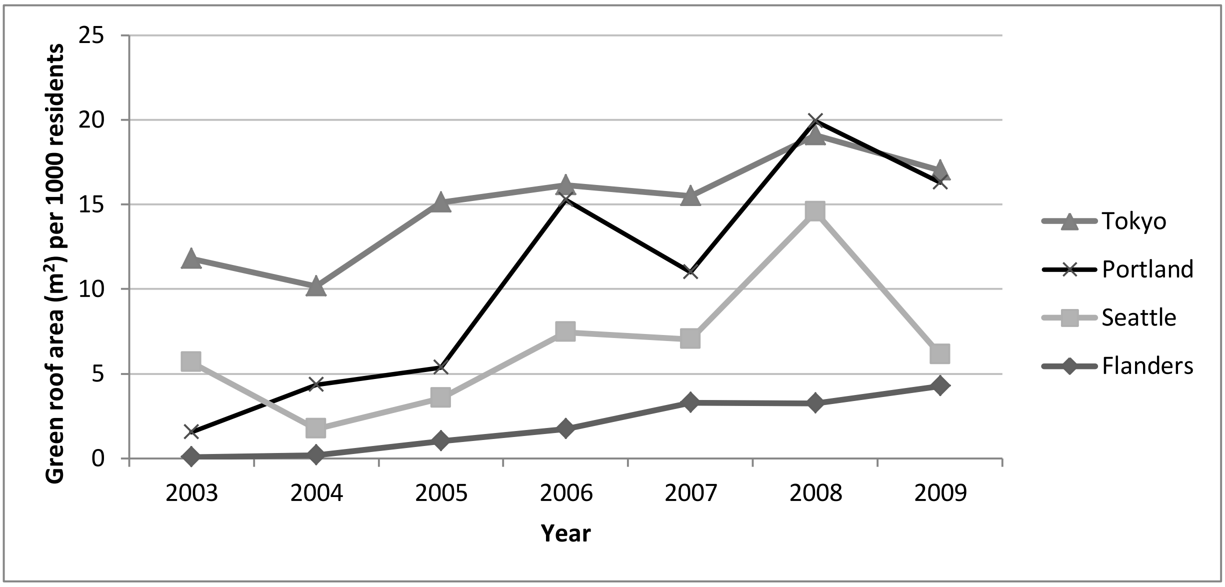

Figure 7.8 Green roof area installed per thousand residents per year, Flanders = subsidised green roofs, Seattle and Tokyo = total green roofs, and Portland = extensive green roofs (McIntosh, 2010, Claus and Rousseau, 2012, Cunningham, 2014, Ministry of Land, 2014).

Both Flanders and Tokyo have adopted relatively consistent forms of incentivisation. In 2001, Tokyo established a law requiring new, extended or renovated developments exceeding 1,000 m^2 (private) or 250 m^2 (public) to green at least 20% of the structural area with the aim of mitigating the UHIE. This law was amended in 2004 to require large scale developments (> 10,000 m^2) to green a percentage of the rooftop area designated by the local authority (Ryokka, 2008, Doi, 2015). As a result of the 2001 law, GR installations per year doubled (from 23,000 m^2 in 2000 to 40,000 m^2 in

2001), while the 2004 requirement that larger developments be greened may account for the further increase in green roof installations occurring between 2004 and 2005 (Figure 7.8).

Flanders, however, adopted a subsidy-based incentive in 2002 (Claus and Rousseau, 2012), which has been credited with the creation of 380 m^2 of green roof in its first year, additional to the 140,000 m^2 already existing, which increased to 6,100 m^2 per annum by 2005. The subsidy was then extended in 2006 to include municipal buildings, resulting in a noticeable boost in subsidised GR installations (Figure 7.8). This represents an almost doubling of subsidised GR area every year, for the years examined, though the total (subsidised and unsubsidised) number of GR installations occurring over this period is unknown (Claus and Rousseau, 2012).

Seattle and Portland represent a more variable approach, with a range of incentives adopted between 2003 and 2009 with the intent of boosting GR uptake. As a background incentive, which appears to have had some success in growing the green roof market, a FAR bonus was offered in Portland from 2001. This was then complemented by a resolution in 2005 requiring that all city owned facilities install green roofs during re-roofing; this trebled the number of green roof installations per thousand residents between 2005 and 2006 (Figure 7.8). An additional boost occurred in 2008 when a financial subsidy was made available, though the amounts offered were decreased in 2012 in order to allow the subsidy to become self-sustaining through revenue collected as stormwater fee payments and fines exacted from non-compliant developers. In Seattle in 2006 the Seattle Green Factor was introduced which stipulated a required percentage of green area for various development types (see section 7.6.1); this was expanded in 2009 with revenues derived from the introduction of stormwater fees, though there was no green roof related rebate until 2016.

In summary, from reviewing the impact of incentives on GR installations, mandatory statutory regulations are likely to represent the most efficient method of encouraging green wall uptake. The creation of regulations is a highly successful method of increasing installation rates, having led to significant increases in GR area in all cities to which it was applied (Ministry of Land, 2014, Irga et al., 2017), because (where inspections and sanctions are enforced) such legislation creates a significant cost for non-compliance. It must, however, be applied with care and full public consultation, not only where ‘top-down’ management is well accepted (such as Japan and Germany), but especially in countries where public outcry can be commonplace such as the UK and USA (Ngan, 2004). Furthermore, depending on the wording of the law, some developers may simply alter development plans to avoid situations that would require greening. Therefore generating an understanding of why these laws are being brought in is vitally important to encourage buy in from both the public and developers. Furthermore, to encourage adherence to the spirit of the laws rather than the letter, it may be wise to allow some degree of flexibility for example, in the form of green space factors (see section 7.6.1). These, when written with a view to improving the overall urban landscape, will enable developers to choose the best greening options for their plans.

Given that mandatory regulations are rarely well received in the UK, and may require a significant period for passage through the legislative system, it is believed that a more nuanced approach would be better suited to local conditions. Subsidies may work well here as they can provide a boost in uptake without creating much controversy (Ofgem, 2017), and similar schemes such as Energy Company Obligations have previously worked well in the UK. They can, however, only fund as many installations as there is money to do so, therefore plans must be included for the subsidy to become self-sustaining (either through levies, taxes or fines), otherwise installation rates can reduce once the incentive is removed (Claus and Rousseau, 2012). Additionally, while a subsidy may increase uptake, it was not found to sufficiently increase the market to reduce installation costs, indicating a possible reduction in installer motivation for improved efficiency (EcoMetrix Solutions Group LLC, 2014), although that may be dependent on length of time subsidy is applied. Subsidies have also been frequently used as a stepping stone towards mandatory regulation, and may therefore represent a ‘softly-softly’ method of reaching a point where more effective measures can be enacted in the UK.

7.7 Conclusion

While there is, as yet, no single commonly accepted framework for analysing the life cycle costs and benefits of structural greening, it appears that direct greening (such as with *Hedera*) currently represents the only consistently sustainable method. This is repeated when considering the outputs of cost-benefit analysis; one of the most commonly used decision-support tools, where the majority of structural greening approaches perform poorly. This problem can be somewhat overcome through a combination of developing a strong local government vision, encouraging stakeholder buy-in (by advertising, if not actively monetising benefits), providing funding for GI installation, and adopting appropriate planning policies. Furthermore, several practical approaches have been established across the globe for reducing the costs or enhancing the benefits of green walls, including legislative encouragement, financial support, public education, and technical assistance. Of these incentives mandatory legislation and subsidies have proven the most successful, albeit only when carefully applied. Therefore, within the UK statutory mandatory legislation with options such as a green space factor with green points scheme may be required to maintain structural greening uptake. However, a multi-phase introduction may encourage engagement within the British setting. Hence, the scheme could be initiated with publicity and additional funding (a direct financial incentive), then followed with mandatory legislation with the threat of fines if the scheme is not upheld. The fines collected could aid in providing financial subsidy until such time as it is no longer deemed necessary, though the subsidy would need to be phased out. This is a similar approach to that used in several British cities, such as London and Southampton.

Chapter Eight

General discussion and concluding remarks

Previous studies have shown that vegetation can alter the microclimatic parameters at the building exterior, providing cooling effects in the summer via shading and evapotranspiration (Cameron et al., 2014) and insulation effects in the winter via reduced air flow (Perini et al., 2011a). Studies have also observed that different plant species produce different cooling and insulation effects based on variations in evapotranspiration rates and depth of foliage (Cameron et al., 2014, Perini et al., 2017a). *Hedera*-covering has been found to insulate building envelopes during cold winters by intercepting rain and snow and shielding the building from wind (Cameron et al., 2015). The factors influencing building microclimate are summarised in Figure 8.1.

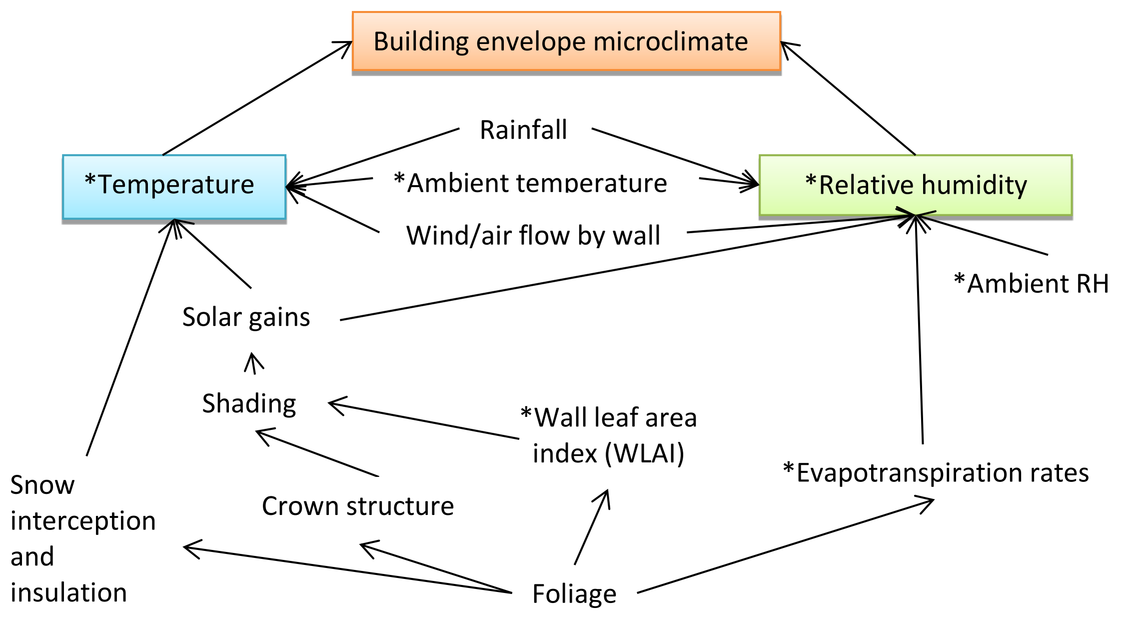

Figure 8.1 Factors influencing building envelope microclimate, * factors were measured in this project

8.1 The impact of plant covering around the building envelope on RH and temperature

Many studies have investigated the cooling effects of *Hedera* on the building envelope during summer (Köhler, 1993, Di and Wang, 1999, Cameron et al., 2014, Hoelscher et al., 2016, Ottelé and Perini, 2017) or looked at similar effects resulting from foliage cladding with other species such as *Parthenocissus* and *Wisteria* (Hoyano, 1988, Cantuaria, 2000, Ip et al., 2010, Pérez et al., 2011a, Susorova et al., 2013, Hoelscher et al., 2016). There are commonly issues with a lack of replication, however (Eumorfopoulou and Kontoleon, 2009, Wong et al., 2010a, Koyama et al., 2013, Zhang et al., 2013), and in those studies with excellent replication; internal temperature and internal RH were not examined or reported (Sternberg et al., 2011a, Cameron et al., 2015). A few studies considered winter conditions in structures with *Hedera*-covering (Sternberg et al., 2011a, Cameron et al., 2015, Ottelé and Perini, 2017) or living wall systems (LWS; (Kronvall and Rosenlund, 2014, Matheus et al., 2016, Djedjig et al., 2017, Ottelé and Perini, 2017)). Very few studies considered alternatives to *Hedera* (for example, evergreen direct greening such as *Pileostegia*) in winter or autumn except Perini et al. (2011a) who included *Pyracantha* as part of mixed planting in an indirect greening option and evergreen plants in a LWS. Within this thesis a robust, replicated, study was conducted that investigated the effects of three different plant species applied as direct greening during summer and winter seasons on the internal and external RH and temperatures of model brick 'buildings'. It was hypothesised that vegetative cover around the buildings would have an effect all year, during both the night and day, therefore it was important to understand the annual 'cycle' of benefits and disadvantages of foliage around buildings.

During hot summer afternoons, foliage around the model 'buildings' (with a half thickness of mortared brick, basic roof and floor insulation), cooled not only the brickwork but also the interior of the 'building'. Internal temperature reductions of up to 7.2 ^{o}C and 4.9 ^{o}C were measured inside the *Hedera*- and *Pileostegia*-covered 'buildings' respectively compared to bare 'buildings'.

The temperature reductions observed within greened model 'buildings' were greater than those observed on buildings with thicker solid wall constructions, such as those examined by Hoelscher et al. (2016) and Eumorfopoulou and Kontoleon (2009) who observed a 1 ^{o}C and 0.9 ^{o}C reduction respectively. When Ottelé and Perini (2017) simulated an 8 hour day at 35 ^{o}C in a CE chamber with a 'typical' wall construction (a cavity wall with insulation), they only found a 1.7 ^{o}C reduction in temperature behind 200 mm *Hedera* foliage, which did not transfer to a difference measured internally. This is in contrast to the experiments in Chapter 3, where the temperatures behind 200 mm *Hedera* foliage averaged at least 2 ^{o}C lower than those measured next to bare 'buildings' (during mean ambient summer daytime temperatures of 18 ^{o}C), this then transmitted into an equivalent 2 ^{o}C decrease in internal temperatures in the greened 'buildings'. Warmer ambient temperatures resulted in greater external and internal temperature reductions for greened 'buildings', indicating less thermal diurnal fluctuation at the wall; hence a stabilising effect.

Although internal temperature differences in greened structures have been measured across 'model' walls within the experiments during summer afternoons, it is likely that a lower internal temperature reduction would be measured if this experiment were repeated using walls on real buildings. Based on the literature this effect would likely be greater for solid walls versus cavity walls (Eumorfopoulou and Kontoleon, 2009, Hoelscher et al., 2016, Ottelé and Perini, 2017).

While foliage cover blocked heating from solar gains during winter, the impact of this was minimal and did not lead to a significant reduction in internal temperature during winter afternoons; any effects would likely be further reduced by a 'typical' wall construction. Similarly in a study of a *Hedera*-covered uninsulated building with a solid wall construction (215 mm thick; twice the thickness of the model 'buildings') during winter, Bolton et al. (2014) found that differences in internal temperature between *Hedera*-covered and bare buildings were within the error of the sensor. This study only monitored the building's north side, however, so the impact of solar gains was not evaluated. The impact of evergreens or LWS have been confirmed through modelling the insulating benefits compared to the blocked solar gains for an LWS on the south side of a building, which showed that an LWS on the south side of a building does not contribute to winter energy savings (Carlos, 2015). The effect of blocked winter solar gains by evergreens on a south wall could be mitigated by using deciduous plants.

During both summer and winter nights, external temperatures were higher behind foliage as the air trapping and thermal properties of the foliage reduced heat loss to the atmosphere. The *Hedera* foliage prevented the most heat loss during the night, though the insulating effect of the brickwork prevented this from transmitting internally; and the use of walls built to domestic or commercial standards would likely further reduce the insulating impact of the foliage. Olivieri et al. (2017) demonstrated that 90 mm of polystyrene insulation reduced the measured temperature reduction due to the presence of an LWS to an insignificant level during summer, though a similar test has not been conducted for winter.

The point at which the cost of retrofitting an LWS would exceed energy savings was investigated by Feng and Hewage (2014a) with a simulation of a LEED gold certified building; while some energy savings were made, the capital investment of installing an LWS was not returned. Additionally thermal benefits derived solely from the use of vegetation as cladding have been shown to be insufficient to convert a 1950-60s building to current building regulations, as further insulation materials (for example, Rockwool) were required (Perini, 2013).

Internal benefits due to *Hedera*-covering on an insulated cavity wall construction have been recorded, but only for a 72 hour period at -5 ^{o}C (Ottelé and Perini, 2017). Therefore, unless ambient winter temperatures average less than -5 ^{o}C it is unlikely that any insulating effect due to the presence of vegetation would be noticed inside a building. This agrees with Bolton et al. (2014) who found that the insulating effect due to ivy increased with colder temperatures.

As plants lose water through evapotranspiration during daylight (predominantly), and do so increasingly as the temperature rises (provided there are no water limitations), it is predictable that the RH measured behind foliage would be higher than that of the bare buildings during the summer afternoons (Pérez et al., 2011a). Evapotranspiration rates do, however, reduce with increased atmospheric RH and reduced solar irradiance (as occur in winter (Allen et al., 1998)); hence the lack of significant differences in measured external RH due to foliage in winter. *Hedera* produced the greatest increase in internal and external RH during summer afternoons, with both *Parthenocissus* and *Pileostegia* producing an intermediate effect. Internal humidity higher than 60% RH is not normally desirable (ASHRAE, 2001), however, during dry summers, higher RH may help cool building interiors and reduce discomfort due to dry air (Miller et al., 2007).

Building envelopes tend to experience high thermal heat loss when temperatures fall overnight, as energy stored in the building materials from solar gains radiates into the atmosphere (Givoni, 1998). As the bare wall temperature drops towards the atmospheric temperature, the RH next to the bare wall is likely to approach the ambient RH (Cantuaria, 2000). However, the presence of foliage reduces this heat loss to the atmosphere by trapping an insulating layer of air next to the wall, which leads to higher temperatures and lower RH compared with those found adjacent to bare walls (Cantuaria, 2000). In the experiments, *Parthenocissus* cladding tended to produce the greatest reduction in external RH over summer nights (though it was rarely statistically significant), while *Hedera* and *Pileostegia* provided a non-significant reduction. This species difference could be explained as the *Parthenocissus* did not increase the RH behind the foliage as much as *Hedera* during the day, so any resulting water vapour in the insulating air layer would be less. Furthermore, *Hedera* typically reduced the external RH over winter nights. Additionally, all plant species increased 'building' internal humidity over summer nights (though only *Hedera* significantly) and generally during winter in 2015. This increase in the internal RH of the vegetation-clad model 'buildings' was likely due to elevated RH values during the day, which remained high at night. Ottelé and Perini (2017) observed, however, that RH increases in *Hedera*-clad structures largely occurred in the cavities of cavity walls. This cavity is present to inhibit moisture from entering the living space by preventing the passage of external water to the internal 'skin' of the cavity wall. Modern cavity walls are also constructed with a condensation-limiting vapour-proof barrier applied behind the insulation of the interior brickwork (Schwartz, 1991). Therefore, direct greening applied to properly constructed or retrofitted buildings is not expected lead to undesirable increases in internal RH.

This study shows that the presence of vegetation significantly stabilised the external and internal thermal environments of model 'buildings' under summer conditions by mitigating the effects of the ambient climate. The vegetation provided these services through shading wall surfaces and via evapotranspiration (Cameron et al., 2014, Vaz Monteiro et al., 2017), the water vapour from which became trapped in stationary air pockets behind the foliage, thus increasing external RH at the building envelope (Perini et al., 2011a).

The same thermal stabilisation trends occurred around *Hedera*-clad 'buildings' over winter but were not statistically significant, likely due to increased cloud cover, reduced day length, solar angle, and solar gains; reducing evapotranspiration rates (Allen et al., 1998). Ambient temperature differences between mornings and afternoons were also smaller in winter than summer (5 ^{o}C compared to 8 ^{o}C, respectively), which would have reduced the impact of any thermal stabilisation further, possibly to statistically insignificant levels. Other studies have also found temperature differences due to the presence of vegetation were less observable during times of intermediate temperatures such as 5-15 ^{o}C, which again coincide with times of low direct solar radiation and evapotranspiration rates, including spring, autumn and mild winters (Perini et al., 2011a, Bolton et al., 2014).

The measurements show that during periods of high solar irradiance, the presence of vegetation is likely to produce more pronounced temperature and RH interactions with buildings. Additionally, thermal impacts of vegetation can be seen during winter temperatures of less than -5 ^{o}C or under an air-gapped layer of snow where a greening induced insulating effect can be observed (Cameron et al., 2015, Ottelé and Perini, 2017). Therefore, given the temperate local climate, the best opportunity for green walls to improve thermal comfort and provide energy savings in the UK would occur in summer, though there may also be some benefits in severe winters.

8.2 Computational modelling of the experimental buildings[3]

In the literature, green walls have mainly been modelled using IES software as part of Masters theses or conference proceedings (Xiangjing, 2011, Alabadla, 2013, Laparé, 2013, Tachouali and Taleb, 2015), and there is a study considering greening as a shading device (Mangone and van der Linden, 2014). There are, however, very few (if any) other peer reviewed papers in which IES is applied to simulate the effects of structural greening. If a validated model of the plant layers involved in direct greening was produced it would then become more feasible to accurately state potential energy

[3] Section 8.2 uses the term 'brick cuboids' to describe the 'model buildings' referred to in other sections and chapters, to avoid confusion with the 'modelled buildings' which were the result of modelling the brick cuboids with building energy software.

savings resulting from plant application (Mangone and van der Linden, 2014). Plants could be considered as part of retrofit energy saving designs, especially for buildings of non-standard construction or those which are difficult to insulate conventionally, as well as from the design stage in construction projects. Specifically a validated plant layer was developed for use in IES as this package bridges commercial and academic interests (Larsen et al., 2015).

A model for the bare brick cuboids was initially designed in IES and validated against the previously gathered experimental data from the bare cuboids (see Chapter 2 section 2.6.1 and Chapter 3 section 3.3). A model plant layer was then developed, based on the *Hedera* plants that surrounded the brick cuboids in Chapter 3. The values for parameters such as specific heat capacity (SHC), density, and thermal conductivity were collected from a mixture of direct measurements and literature (including Hays (1975), Jayalakshmy and Philip (2010), and Jones (1992); see Chapter 4 section 4.2.4). These values were used to construct a new material in the IES-material database, and simulations of supplementary claddings were compared against experimental data to determine the extent to which modelled trends matched 'real-world' findings.

The simulated temperature profile for the plant layer which was based on the maximum values for SHC etc. ('*Hedera* max') were less accurate than those based on minimum values ('*Hedera* min'), when compared to experimental trends. This difference between the simulated temperature profiles probably occurred because the '*Hedera* max' layer stabilised the internal environment more than was found in the experiments, due to the lower thermal diffusivity (hence increased thermal inertia) resulting from the values utilised. Therefore, the '*Hedera* min' layer was used and accurately represented the experimental temperature profile during summer and winter simulations.

The importance of an accurate weather file for validating simulated model comparisons to an experimental model was highlighted by this research, especially in the case of bare buildings or reference models. This has been a common problem in other simulation validation studies (Xiangjing, 2011, Alabadla, 2013, Laparé, 2013). Most of variation in trends resulting from issues with weather files could be reduced by using data from the areas in which experiments were conducted. Furthermore, modelling the 'buildings' with different weather files then comparing simulated and experimental results showed that the minimum number of measured parameters required for a weather file to improve the accuracy of simulated structures were the dry bulb temperature, RH (or wet bulb temperature), and dew point (which could be calculated from the dry bulb and RH/wet bulb temperature). Therefore, even a few simple weather measurements made *in situ* during an experiment may substantially improve model validation with building energy software. When a full year of weather for an experimental site was used, however, some trends that had been inaccurately predicted using a partial weather file were modelled more accurately.

Despite these limitations, the modelling and thermal simulation software IES, was able to accurately simulate the internal south wall surface temperature profile during the two experimental periods (summer and spring/winter), indicating the excellent capacity of this tool. Additionally, when the *Hedera* layer was simulated the resulting data matched the experimental data equally accurately.

As a result of producing a validated plant-based layer within IES software, direct greening, especially with *Hedera* can now be modelled and simulations run to analyse the potential energy savings due to the use of vegetation around buildings. These simulations could be conducted for a range of building specifications and in different locations to find the situations where direct greening would have the greatest impact.

8.3 Reducing ivy aerial root attachment with metals and anti-graffiti paints

One of the most common issues surrounding the use of *Hedera* for direct greening is the species' tendency to damage or invade lime mortar and structure fixtures such as gutters (Köhler, 2008, Douglas & Noy, 2011). Therefore, methods of reducing the ability of *Hedera* to attach to walls were investigated, with a view to developing a management strategy.

The attachment mechanisms of *H. helix* aerial roots have been explored by Melzer et al. (2009) who composed a list of the *Hedera* attachment properties of different materials; those materials to which *Hedera* was unable to attach (potentially due to toxicity and surface smoothness (Arnold and Struve, 1993, Baker et al., 1995, Dunnett and Kingsbury, 2008)), included metal, glass and ceramics (Melzer et al., 2009). Further work on the attachment of *Hedera* aerial roots discovered that the adhesive substance they produce contains nanoparticles (Zhang et al., 2008). It was hypothesised that the hydrophobic and lipophobic (oil and water repelling) silica nanoparticles, silanes, contained within some anti-graffiti paints could reduce *Hedera* aerial root attachment by acting at the same spatial scale as the *Hedera* adhesive nanoparticles. Therefore some of these materials (anti-graffiti paints, zinc, copper plate and mesh) formed the basis of work on reducing aerial root attachment around buildings in *Hedera helix* and *H. hibernica*.

In laboratory experiments, metals (copper and zinc) appeared to be the material that most reliably prevented aerial root attachment in both *H. hibernica* and *H. helix*. While sheet copper and zinc were trialled in the laboratory experiment, fine copper mesh was equally effective in the field-based experiment, which suggests that it could provide a cheaper practical alternative for most construction settings. Nonetheless, metals are still relatively expensive (both reducing their likelihood of use and increasing their vulnerability to theft); therefore metal paints have been suggested for future research as an even cheaper, theft-resistant alternative for use on buildings.

Interestingly, *H. hibernica* attached (weakly) to the silane-based anti-graffiti paint, whereas the paint inhibited *H. helix* attachment, indicating that there may be a difference in the composition of the adhesive substance secreted by the aerial roots of different species of *Hedera*. Research performed by others has shown that attachment strengths differ between plant species, from 4 N for *H. helix* attached to bark to 18 N for *Campsis radicans* (trumpet vine) attached to wood (Steinbrecher et al., 2010). Differences between species of the same family have not been tested, however, nor have the attachment strengths of plant species when attached to the same substrate. Additionally, while the attachment strengths of *H. helix* aerial roots on materials such as cork, tree barks of seven tree species, and plaster or mortar were assessed, the force required to detach the ivy was not reported by the experimenters (Melzer et al., 2012). This data, taken together does, however, indicate that attachment management strategies could be adapted to different *Hedera* species, depending on the strength and composition of their adhesive secretions. In the field-based experiment, however, the ivy was able to reattach to the wall beyond the deterrent height of 300 mm (Figure 8.2), suggesting that either the deterrent must cover a greater height or the ivy must be pruned before it starts to grow over the deterrent. When the ivy grew over the copper, it actively avoided touching the metal (which can be observed in Figure 8.2, where the ivy bends away from the metal mesh) which would make pruning easier. It is unclear whether the anti-graffiti paint would prevent *Hedera* attachment over brickwork (as opposed to cork panels tested in this project), as bricks have a rough surface which may not be fully covered by the paint, therefore, the ivy may be able to attach in spite of the reduction in attachment strength. It is likely, however, that the stem detachment force would be reduced where anti-graffiti paint was used, making maintenance and pruning easier. Additionally anti-graffiti paint should, also, prevent the scarring effect of root attachment on wall surfaces, thus reducing the need to clean the wall after ivy removal. All these hypotheses require further testing.

The method of testing attachment strength with cuttings was a useful screening process, where multiple materials and different species or cultivars of ivy could be tested in around 10 weeks. It may, therefore, have some application as a rapid standardised test in industry. The experiments also show, however, that materials which prevent aerial root attachment in a laboratory setting need to be validated with established plants, as the silane anti-graffiti paint completely prevented aerial root attachment in *H. helix* in the laboratory but only reduced the strength of attachment in the field.

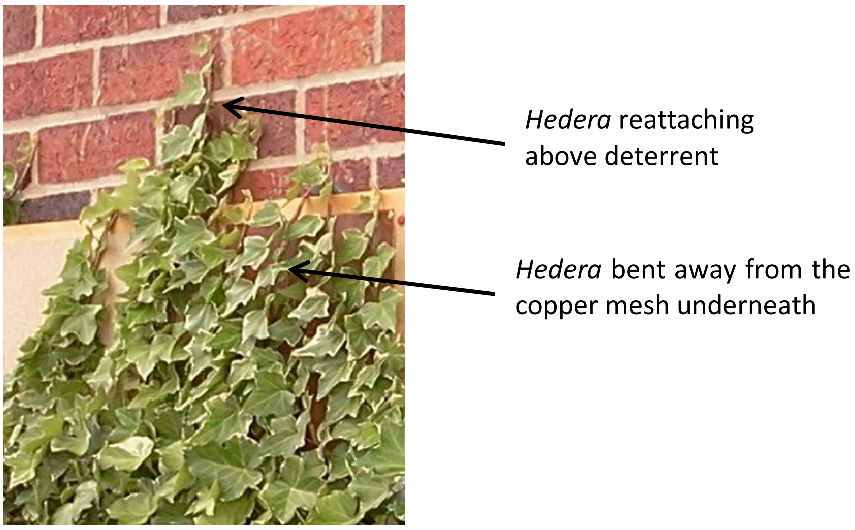

Figure 8.2 *Hedera helix* growing over metal deterrent

8.4 Water deficit and root restriction interactions on growth and aerial root production

The impacts of water deficit and root restriction on ivy growth and aerial root production were studied as climbers growing next to buildings, either in trenches or containers, are likely to encounter root restriction and water deficit due to soil compaction or the impervious nature of structures (such as buildings and foundations) around them (Dunnett and Kingsbury, 2008). Since buildings create a rain shadow and unless the planting is part of a rain garden, choosing plants that are resistant to drought is advisable as it reduces the need for regular watering, especially as irrigation frequently uses potable water (Dunnett and Kingsbury, 2008). Climbers (such as *Hedera*) are suitable for planting next to buildings as their roots do not routinely damage foundations and are not covered by the High Hedges Act (Royal Horticultural Society, 2018b). In order to establish appropriate plants for direct greening it may, therefore, be advisable to test the effects of drought and root restriction on candidate species.

Root restriction studies on peach (Richards and Rowe, 1977) and pepper (Ismail and Davies, 1998) have shown reduced above ground growth in plant height and leaf number under restricted conditions. Additionally, cumulative shoot growth was reduced by 80-94% in root restricted compared to unrestricted cherry and apple trees (Webster et al., 1997, 2000), with an additional 24% reduction in leaf area in the root restricted apple trees (Webster et al., 2000). Conversely, additional irrigation increased shoot growth of unrestricted trees by one and a half to twice the controls and around three times the growth of root restricted trees (Webster et al., 2000), indicating that both the controls and the root restricted trees were suffering some water deficit. Furthermore, water deficit studies have shown reduced above ground growth for plant height in safflower (Hojati et al., 2011) and leaf number in eucalyptus (Osório et al., 1998). As would be expected, combining root restriction and water deficit further reduced above ground biomass production (Poorter et al., 2012) and leaf number (Dambreville et al., 2016). However, the effects of root restriction and water deficit have not been directly studied in *Hedera* with respect to shoot and aerial root growth, nor have the combined effects been studied on adventitious root growth, therefore these experiments may have implications for ivy management, especially after a drought.

The combined effect of root restriction and water deficit reduced above ground growth, and aerial root production in *Hedera*, although the attachment strength was not tested. Therefore *Hedera* may require pruning or supporting after a drought period, as its attachment strength may be weakened due to water deficit. Managing *Hedera* in this way would be an important part of maintenance, especially in the urban environment, given that damage by plants to people or property must be paid for by the owner of the plant (Royal Horticultural Society, 2018c). Additionally, the growth and attachment of *Hedera* may be managed by planting specimens in large containers in the ground, surrounded by root barriers to prevent the roots encroaching into the surrounding earth. Due to the persistence of *Hedera* roots in finding water sources, however, this may only restrict plants for so long before they penetrate the barrier or grow underneath to find new water sources. Many other climbing plant species such as *Wisteria* can be planted in deep planters with irrigation (500 mm deep), and provide sufficient growth to green façades and produce cooling benefits (Köhler, 2008). Planted containers would not stop *Hedera* trailing across the ground to root elsewhere, however, so further management techniques (for example, twining stems up trellises) would be required to keep the *Hedera* growing up the wall.

8.5 Sustainability and economics relating to green walls and the policy and incentives of green wall implementation

The green wall sector in the UK has developed considerably over this EngD project, with an increasing number of green wall installation case studies added to the installation companies' portfolios every year. The number of case studies available has grown from 18 across the UK in 2012 to 34 in 2017, which may indicate that the sector has nearly doubled over the last five years (though the case studies do not account for all installations and not all wall greening companies were accessed). While some studies have used life cycle assessment (LCA) to investigate the sustainability of green walls, in the UK, only direct greening (such as self-attaching *Hedera*) and indirect greening (using climbing plants and a plastic support trellis) appear to be environmentally sustainable (Pan and Chu, 2016, Ottelé and Perini, 2017). According to the LCA, all other more engineered forms of living walls (such as climbing plants with steel supports/trellis, modular planter based or geotextile LWS), were not environmentally sustainable in the UK because emissions saved due to the cooling benefits of greening in summer over the lifetime of the wall did not mitigate the emissions generated to create the living wall (Ottelé et al., 2011). The preferential uptake of direct greening could therefore be encouraged on the basis of sustainability credentials. Given that the results of a LCAs performed on the same product can vary significantly depending on input data and output analysis, therefore it may be necessary to develop a standard LCA for the UK. This could both encourage the uptake of the direct and indirect greening styles on the basis of their better sustainability credentials, encourage higher standards in green wall installers, and form the basis of a system of regulations.

The financial barriers to green façade installations are fewer than those of living walls, suggesting that their widespread uptake is likely to hold greater appeal. There are, however, several barriers to green façade and living wall installation. Arguably the strongest of these is that when living walls are analysed with a common decision support tool; the CBA, the costs typically outweigh the benefits. Approaches to reduce financial barriers to green walls may include monetising their benefits (such as improvements in atmospheric quality or energy savings from cooling the building exterior), providing subsidies and improving the cost efficiency of installation. The funding streams used to finance green walls are complicated, often involving multiple organisations (Mobilane UK Ltd., 2018a). As living walls specifically have high capital and maintenance costs, they frequently require particularly complex funding arrangements.

Currently the benefits of GI are starting to be monetised within the urban environment (Groundwork London and Hammersmith & Fulham Council, 2016); therefore it may be beneficial to start to consider GI in terms of marketable commodities. To boost sales, marketing based on the niche which a product fills can be used to focus attention on the service provided by that product to gain leverage either within a market or to establish a market (Moore, 2014). While the benefits of GI are that they provide many ecosystem services simultaneously (Dover, 2015), having a primary selling or marketing point appears beneficial for incentivising uptake, though doing so may hide the holistic benefits of GI. If a primary monetisable or motivational benefit were to be used, it ideally needs to prevent a costly problem (such as surface water flooding, the UHIE or climate change), which GI has proven efficient in tackling. For example, the primary monetisable benefits used to encourage the planting of street trees have been pollution capture and mitigation of the UHIE, both of which (atmospheric pollution and high temperatures) cost lives and money (Setälä et al., 2013, Defra, 2015, Skelhorn et al., 2016, Chen et al., 2017). Similarly, the primary monetisable benefits of green roofs are their rainwater or stormwater attenuation capacities, tendency to mitigate the UHIE, and ability to reduce ecosystem degradation in the urban environment. These benefits have been used to drive green roof uptake and mandatory policy in cities in many places such as Europe, Japan, America, and Canada (Peck et al., 1999, Townshend and Duggie, 2007).

For green walls to be incentivised efficiently a sellable benefit needs to be found, and from the case studies and literature the most likely candidates in the urban environment are particulate capture and improved local wellbeing. Particulate pollution cost lives and the NHS thousands of pounds (Defra, 2015) and green corridors expose residents, customers, and employees to high quality and varied green spaces, thus improving their overall productivity and wellbeing (therefore increasing local house prices and the tendency of customers to spend money at a location; (ECOTEC Research and Consulting, 2008)). Due to their surface area, position, and therefore ability to add GI without sacrificing building footprint by greening the façades of street canyons, green walls represent a relatively space efficient method of achieving these benefits (Pugh et al., 2012).

There are some examples of green walls installed specifically for particulate capture, funded by Transport for London (TfL), and the aim of which (along with traffic calming methods) was to improve air quality in some of London's most polluted areas (Shackleton et al., 2012, ANS Global and Chambers, 2018b). Additionally green walls have been planted near playgrounds of several schools in London to reduce the impact of pollution on school children (Tremper and Green, 2018).

Based on previous schemes used to increase the installation rate of green roofs (GRs), there are many different options available for green walls; two methods used to successfully encourage installations are policies and incentives. Policies include statutory policies, which stipulate GR installation (as per Hong Kong, where all new public buildings must have green roofs; Irga et al. (2017)) or allow options to be chosen (such as GSF and its equivalents as in Malmö and Seattle: ASLA (2010), LaClergue (ca. 2014), Dover (2015)). Additionally non-statutory policies and guidelines can encourage greening actions (such as the All London Green Grid; GLA (2012)). Financial incentives include direct financial incentives (subsidies), which are the most widely used form of incentivisation, and indirect financial incentives, such as reduced stormwater fees in Portland, USA (Townshend and Duggie, 2007), expedited planning permission in Chicago, USA (Kazmierczak and Carter, 2010), tax credits in New York and Maryland, USA (Plant Connection Inc., 2018), and density bonuses in Austin, Texas and Arlington County, Virginia; USA (Plant Connection Inc., 2018). There are a variety of supporting activities which also act as incentives, including favourable credit terms for the greening activity, demonstration projects, ecological labels (such as LEED certification), media support, local green roof guidelines, and consultancy services. Additionally, research and education in the form of seminars, conferences, tours and competitions all supported and build interest and confidence in the industry. Typically a combination of incentives was required to promote GR installations and would likely be required for green walls too.

Several factors may be considered when choosing which incentive to use (Ngan, 2004). Cultural attitudes may have an additional subtle effect, and it is therefore important to be aware of how people in different cities may react to incentives and governmental methods (such as top-down versus bottom-up). For example, cultural differences may have explained why in Japan and Stuttgart (Germany) mandatory regulations and fines for non-compliance worked well, with no additional penalties required (Peck et al., 1999, Townshend and Duggie, 2007), whereas, voluntary regulations and occasional direct financial incentives have worked in London, UK (Ranade et al., 2012). Not only do cultural attitudes to government regulations matter in choosing between voluntary and mandatory incentivisation schemes, but also the sense of choice and consultation, the number of people affected (Thurston, 2014), and economic factors (Segerson, 1999).

Furthermore, while subsidisation works best when money available for the subsidy is partially self-sustaining, such as the 5% levy on energy bills implemented in Basel, Switzerland which was then used to subsidise GR (Kazmierczak and Carter, 2010); stakeholder consultation is required to assess public reaction to such a potentially controversial policy. The importance of some form of governmental policy, even non-statutory, has been highlighted in a study which showed that cities in Australia with local policies encouraging GR uptake installed more GRs than those without (Irga et al., 2017). Contrary to most studies, Köhler (2015) recommended using supporting activities, such as creating detailed guidelines rather than legislation, as these appeared to have the greatest impact on incentivisation, though their data only extends to Germany.

A mandatory options based scheme such as a green space factor with green points scheme may be both accepted and necessary to increase structural greening installations and improve urban green infrastructure, as part of mitigating climate change and improving air quality and quality of life in the urban environment. While greening in London using non-statutory policies (based on a combination of public-private partnership, funding availability and cross-authority cooperation) has proven effective (resulting in the installation of at least 1,012 m^2 of green walls), other mandatory policies are also being developed to increase uptake such as the urban green factor for London (GLA, 2016, 2017b). Funding schemes are not, however, known to be available to private homeowners, who must currently fund green wall installations from their own resources, which appears to be an oversight.

In order to save money and ensure that any incentive used has the greatest possible impact, however, the infrastructure, interest and knowledge to support the industry need to be in place, ideally before an incentive scheme is released. While knowledge and understanding of prior mistakes, either in other countries or in related industries may prevent some hazards, there will be a risk of unqualified traders capitalising on a growing market, especially if financial incentives have rapidly boosted growth. Therefore tight trading standards and rigorous technical guidelines, along with some form of accreditation, could protect ‘good traders’ and customers (Ngan, 2004).

8.6 Future work

8.6.1 Temperature and RH impacts of ivy around different building constructions

The RH, as measured in Chapter 3, can be used to calculate dew points and measurements of air saturation, which is why it is frequently used in a construction context. Humidity can also be measured in absolute terms, however, which is a measurement of the mass of moisture per volume of air. Therefore, future measurements of absolute humidity would show whether the reduced RH behind *Parthenocissus* versus *Hedera* foliage was due to an actual reduction in air moisture content, an increased temperature or a combination of these factors.

Additionally it would be interesting to measure the thermal/RH impact of a single plant species, such as *H. helix,* on multiple different common constructions found in the UK housing stock, including solid walls and constructions of non-standard nature (such as Wimpey no-fines, ‘prefabs’, and concrete homes; Ross (2002)), which can be more expensive to insulate. The hypothesis would be that as these buildings typically require external wall insulation, and can suffer from damp if ‘sealed’ and not allowed to ‘breathe’ *Hedera*-cladding may offer energy savings and become a suitable alternative to external insulation. Furthermore, there may be a greater probability of direct greening negatively impacting buildings with less ventilation or poor quality cavity wall insulation, something that would require investigation in order to prevent the installation of green walls on unsuitable surfaces.

Furthermore, it may be useful in the future to track energy use for winter heating in greened versus bare buildings, especially in cases where the south wall is left uncovered, which could be tested both empirically and through simulations.

8.6.2 Modelling parameters for building simulations

The importance of solar irradiance on internal temperature was made apparent by the modelling of buildings in IES; it would therefore be useful to measure the hourly range of solar irradiance on the north and south sides of the model 'buildings'. There may also have been local microclimate effects due to air flow around the model 'buildings'; therefore, it would be worth investigating the effects of wind direction and strength on the RH and temperature parameters of the model 'buildings' in order to establish forcing variables on structures' air-tightness.

Furthermore, it would be beneficial to determine which weather parameters have the greatest impact on basic model validation, as they may provide a basis for the minimum number of weather parameters requiring measurement during experiments which are likely to be later be modelled. Additionally, an investigation of the impact of a full weather file, versus sections of data relating to the time of an experiment, would be helpful, as it is often easier to obtain data for an experimental period than a full year.

As values for the parameters of the *Hedera*-layer were derived experimentally and from literature, it would have been useful to have had another year of experimental data to check whether the modelled *Hedera* behaved as expected for different weather conditions. In a future study, it would be interesting to compare the 'extra room with HVAC' method (Laparé, 2013) to the *Hedera*-layer created in Chapter 4 to test which of these most closely represents the temperature profile of the experimental 'buildings', as the extra room with HVAC has more scope to characterise the plants dynamic cooling mechanisms. It would also be useful to develop plant layers that represent other plant species, in order to provide a range of options that could be used when considering plants as part of passive cooling strategies. Additionally the *Hedera*-layer could be simulated on structures with heating and cooling to investigate the energy savings could be achieved by plant installation.

8.6.3 Inexpensive alternatives for reducing *Hedera* aerial root attachment

To reduce the cost impacts of materials used to prevent *Hedera* attachment, alternative paints and different sized metal meshes could be trialled. Antifouling paints, which prevent algal build up on the bottom of boats, frequently contain copper powder or copper salts which may have an adverse effect on aerial root attachment as could galvanised steel mesh and copper with larger mesh sizes. It would also be wise to carry out building scale trials to establish whether potential methods could be scaled up, and perform trials of anti-graffiti paint using facing bricks on plywood to determine whether the additional roughness of brick enables *Hedera* aerial roots to attach strongly despite the treatment. There were indications, during the experimental phase of this thesis, that different *Hedera* species (such as *H. helix* and *H. hibernica*) have different adhesive compositions and strengths, which may mean that different management solutions are required for different species. It would, therefore be advisable to investigate the adhesive composition of different *Hedera* species and whether that makes them more or less manageable.

Lastly, as a method for testing the strength of *Hedera* attachment has been developed, it would be useful to test the strength of ivy attachment under water deficit and root restriction. This would determine whether root restriction (potentially applied by root pruning techniques such as trenching) affects *Hedera* attachment *in situ*.

8.6.4 Standards for green wall implementation

To encourage the uptake of direct greening (and green walls generally) it would be useful for homeowners, councils and housing associations, along with landscape designers, to have a set of criteria and a rationale that could recommend whether a building is suitable for a green façade. The criteria could include factors such as the age of the construction, mortar type, and construction type, and could be produced after further modelling and experimental investigation such as recommended above. Collaboration with experts in the fields of building restoration, construction, and surveying would also be advisable to ensure that any set of criteria covered all possible bases. Any such criteria or rationale could be sponsored/published by organisations such as Royal Horticultural Society (RHS), Chartered Institute of Building Services Engineers (CIBSE), BRE (Building Research Establishment), or Royal Institute of British Architects (RIBA) in collaboration with the green wall centres around the UK.

Alongside that, a technical standard for living walls including criteria such as construction requirements, plant types, wall suitability and reinforcement methods, and typical plant irrigation volumes and management requirements (pruning frequency and methods, pest and disease management) would increase confidence in living walls and provide a baseline for all living wall companies to adhere. The technical standard could be based on the German or Viennese façade greening standards (Enzi et al., 2014, FLL, 2018). It is hoped that this and any future work conducted will encourage the creation of such a standard.

References

Ackerfield, J. & Wen, J. (2003). Evolution of *Hedera* (The ivy genus, *Araliaceae*): Insights from chloroplast DNA data. *International Journal of Plant Sciences,* **164,** 593-602.

Ackerman, F. (2008). *Critique of cost-benefit analysis, and alternative approaches to decision-making.* London: Friends of the Earth England, Wales and Northern Ireland

Airqualitynews.com. (2018). *Green screens 'effective' in reducing NO2 pollution*. URL: https://www.airqualitynews.com/2018/02/12/green-screens-effective-in-reducing-no2-pollution/: [24/09/2018].

Ajuntament de Barcelona (2013). *Plan del Verde y de la Biodiversidad de Barcelona 2020.* (Green plan and biodiversity Barcelona). Barcelona: Ajuntament de Barcelona

Ajuntament de Barcelona. (2018). *Green roof competition*. URL: http://ajuntament.barcelona.cat/ecologiaurbana/en/green-roof-competition: [27/05/2018].

Akbari, H. & Konopacki, S. (2005). Calculating energy-saving potentials of heat-island reduction strategies. *Energy Policy,* **33,** 721-756.

Alabadla, M. (2013). *A study on reducing heat gains through the use of green envelope.* MSc Dissertation. The British University in Dubai (BUiD). URL: https://www.witpress.com/elibrary /wit-transactions-on-ecology-and-the-environment/193/33920: [27/02/2018]

Albert, L. (2010). *Under quarantine: Ivy, butterfly bush, scotch broom and their cultivars face tough new state rules*. URL: http://www.oregonlive.com/hg/index.ssf/2010/03/under_quarantine _ivy_butterfly.html: [23/03/2013].

Alexander, S. & Greber, B. (1991). *Environmental ramifications of various materials used in construction and manufacture in the United States.* (General Technical Report PNW-GTR-277). Portland, OR: Forest Service of the US Department of Agriculture. URL: https://www.fs.fed.us/pnw/pubs/pnw_gtr277.pdf: [13/07/2018]

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

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. (1998). *Crop evapotranspiration-Guidelines for computing crop water requirements* (FAO Irrigation and drainage paper 56). Rome: FAO (Food and Agriculture Organization of the United Nations). URL: https://appgeodb.nancy.inra.fr/biljou/pdf/Allen_FAO1998.pdf: [18/02/2019]

Alyami, S. H. & Rezgui, Y. (2012). Sustainable building assessment tool development approach. *Sustainable Cities and Society,* **5,** 52-62.

Anderson, J. Shiers, D. & Steele, K. (2009). *Green guide to specification*. 4th ed. Chichester: Wiley-Blackwell.

ANS Global & Chambers, M. (2018a). *Living wall case studies*. URL: https://www.ansgroupglobal.com/living-wall/case-studies. [21/05/2018]

ANS Global & Chambers, M. (2018b). *Transport for London*. URL: https://www.ansgroupglobal.com/living-wall/case-studies/transport-london: [21/05/2018].

Ansel, W. (2018). IRGA city network case studies. (email, personal communication, 01/08/2018)

Ansel, W. & Appl, R. (2014). *Green roof policies—an international review of current practices and future trends.* Nürtingen: International Green Roof Association (IGRA). URL: https://www.nparks.gov.sg/-/media/cuge/ebook/citygreen/cg2/cg2_02.pdf: [18/02/2019]

Ares, E. (2016). *Zero carbon homes.* (Briefing paper 6678). London: House of Commons Library. URL: researchbriefings.files.parliament.uk/documents/SN06678/SN06678.pdf: [18/02/2019]

Aretis, A., Lord, C., Minkler, R., Revill-Darton, S., Penston, R. & Whittington, M. (2015). *Baker street quarter BID greenery action plan.* London: Publica. URL: http://www.bakerstreetq.co.uk/ wp-content/uploads/2017/06/Greenery-Action-Plan-Web-Ready-Final.pdf: [18/02/2019]

Arkles, B., Pan, Y. & Kim, Y. M. (2009). The role of polarity in the structure of silanes employed in surface modification. In: K. L. Mittal ed. *Silanes and other coupling agents Volume* 5. Leiden: Koninklijke Brill. pp. 51-64

Arnold, C. L. & Gibbons, C. J. (1996). Impervious surface coverage: The emergence of a key environmental indicator. *Journal of the American Planning Association,* **62,** 243-258.

Arnold, M. A. & Struve, D. K. (1993). Root distribution and mineral uptake of coarse-rooted trees grown in cupric hydroxide-treated containers. *HortScience,* **28,** 988-992.

Arnold, M. A. & Young, E. (1991). $CuCO_3$-painted containers and root pruning affect apple and green ash root growth and cytokinin levels. *HortScience,* **26,** 242-244.

Ashford, N. A. (1981). Alternatives to cost-benefit analysis in regulatory decisions. *Annals of the New York Academy of Sciences,* **363,** 129-137.

ASHRAE (2001). *ANSI/ASHRAE Standard 62–2001 Ventilation for acceptable indoor air quality.* Atlanta, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers Inc. (ASHRAE)

ASLA (2010). *Seattle green factor.* Seattle, WA: American Society of Landscape Architects (ASLA). URL: https://www.asla.org/2010awards/519.html: [11/02/2019].

Atwell, B. J., Kriedemann, P. E. & Turnbull, C. G. N. eds. (1999). *Plants in action: Adaptation in nature, performance in cultivation*. South Yarra: Macmillan Education Australia.

Ayres, R. U. (1995). Life cycle analysis: A critique. *Resources, Conservation and Recycling,* **14,** 199-223.

Azkorra, Z., Pérez, G., Coma, J., Cabeza, L. F., Bures, S., Álvaro, J. E., Erkoreka, A. & Urrestarazu, M. (2015). Evaluation of green walls as a passive acoustic insulation system for buildings. *Applied Acoustics,* **89,** 46-56.

Bailey, W. G., Oke, T. R. & Rouse, W. eds. (1997). *Surface climates of Canada*. Montreal: MQUP.

Baker, J. F., Burrows, N. L., Keohane, A. E. & de Filippis, L. F. (1995). Chemical root pruning of kangaroo paw (*Anigozanthos flavidus*) by selected heavy metal carbonates. *Scientia Horticulturae,* **62,** 245-253.

Barnett, J. P. & McGilvray, J. M. (1974). Copper screen controls root growth and increases survival of containerized southern pine seedlings. *Tree Planters' Notes*, **25 (2),** 11-12.

Bauer, H. & Bauer, U. (1980). Photosynthesis in leaves of the juvenile and adult phase of ivy (*Hedera helix*). *Physiologia Plantarum,* **49,** 366-372.

BBC (British Broadcasting Corporation) (2018). *UK's most polluted towns and cities revealed*. URL: https://www.bbc.co.uk/news/health-43964341: [12/07/2018].

Beaufoy, S. (1947). *Butterfly lives*. London: Collins.

Beccaro, G. L., Cerutti, A. K., Vandecasteele, I., Bonvegna, L., Donno, D. & Bounous, G. (2014). Assessing environmental impacts of nursery production: methodological issues and results from a case study in Italy. *Journal of Cleaner Production,* **80,** 159-169.

Beckett, K. P., Freer-Smith, P. H. & Taylor, G. (2000). Particulate pollution capture by urban trees: effect of species and windspeed. *Global Change Biology,* **6,** 995-1003.

Beeson Jr, R. C. & Newton, R. (1992). Shoot and root responses of eighteen southeastern woody landscape species grown in cupric hydroxide-treated containers. *Journal of Environmental Horticulture,* **10,** 214-217.

Bernstein, L., Huq, S., Matsuno , T., Palutikof, J., Rosenzweig, C., Sugiyama, T., Bosch, P., Karoly, D., Menne, B., Parry, M., Rusticucci, M., Swart, R., Canziani, O., Kattsov, V., Metz, B., Qin, D., Schneider, S., Tirpak, D., Chen, Z., Kundzewicz, Z., Mirza, M., Ravindranath, N., Sokona, Y., Vogel, C., Christ, R., Liu, J., Nicholls, N., Reisinger, A., Solomon, S., Yohe, G., Davidson, O., Lohmann, U., Nurse, L., Ren, J., Stott, P., Hare, W., Manning, M., Pachauri, R., Riahi, K., Stouffer, R. & Barker, T. (2007). *Climate Change 2007 : Synthesis Report. An Assessment of the Intergovernmental Panel on Climate Change*. Valencia: Intergovernmental Panel on Climate Change.

Bingham, C., Walsh, C. & Carroll, S. (2012). Impact of driving characteristics on electric vehicle energy consumption and range. *IET Intelligent Transport Systems*, **6,** 29-35

Biotecture Ltd. (2018). *Portfolio*. URL: http://www.biotecture.uk.com/portfolio/: [24/03/2018 2018].

Bischoff, I., Eckelt, E. & Kuhlmann, M. (2005). On the biology of the ivy-bee *Colletes hederae* Schmidt & Westrich, 1993 (Hymenoptera, Apidae). *Bonner zoologische Beitrage,* **53,** 27-36.

Blanuša, T., Fantozzi, F., Monaci, F. & Bargagli, R. (2015). Leaf trapping and retention of particles by holm oak and other common tree species in Mediterranean urban environments. *Urban Forestry & Urban Greening,* **14,** 1095-1101.

Blanuša, T. and Thomsit-Ireland, F. (2017). Ecosystem services. In: McAllister, H. & Marshall, R. *Hedera: The complete guide.* London: Royal Horticultural Society (RHS), pp. 85-96.

Blanuša, T., Vaz Monteiro, M. M., Fantozzi, F., Vysini, E., Li, Y. & Cameron, R. W. F. (2013). Alternatives to sedum on green roofs: Can broad leaf perennial plants offer better 'cooling service'? *Building and Environment,* **59,** 99-106.

Bodkin, H. (2017). Trees trap pollution in congested city streets - plant hedges instead, study finds *The Telegraph*. (Last updated 3:11pm on 17 May 2017)
URL: https://www.telegraph.co.uk/news/2017/05/17/trees-trap-pollution-congested-city-streets-plant-hedges-instead/: [19/02/2019]

Bolton, C., Rahman, M. A., Armson, D. & Ennos, A. R. (2014). Effectiveness of an ivy covering at insulating a building against the cold in Manchester, U.K: A preliminary investigation. *Building and Environment,* **80,** 32-35.

Bolund, P. & Hunhammar, S. (1999). Ecosystem services in urban areas. *Ecological Economics,* **29,** 293-301.

Bradford, K. J. & Hsiao, T. C. (1982). Physiological responses to moderate water stress. In: Lange, O. L., Nobel, P. S., Osmond, C. B. & Ziegler, H. (eds.) *Physiological Plant Ecology II: Water Relations and Carbon Assimilation.* Heidelberg: Springer-Verlag.

Bradley, P., Coke, A. & Leach, M. (2016). Financial incentive approaches for reducing peak electricity demand, experience from pilot trials with a UK energy provider. *Energy Policy,* **98,** 108-120.

BRE (Building Research Establishment), Construction Research Communications Ltd & Building Research Establishment Executive Agency (1996). *Bird, Bee and Plant Damage to Buildings*. London: Construction Research Communications.

BritishBIDs. (2018). *BID Locations*. URL: http://britishbids.info/bid-locations/: [11/02/2018].

Bruhns, H. (2008). Identifying determinants of energy use in the UK nondomestic stock. In: Internation conference on improving energy efficiency in commercial buildings "IEECB '08". Frankfurt, 10-11 April 2008. Luxembourg: Publications Office of the European Union

Bruse, M. & Fleer, H. (1998). Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environmental Modelling & Software,* **13,** 373-384.

Burgess, P. A. (2015). *Analysis of Historical Solar Irradiance Data And Development of A Virtual Pyranometer Method For Real-Time PV Monitoring.* EngD Thesis, University of Reading.

Burris, J. N., Lenaghan, S. C., Zhang, M. & Stewart, C. N. (2012). Nanoparticle biofabrication using English ivy (*Hedera helix*). *Journal of Nanobiotechnology,* **10,** 1-7.

Calfapietra, C., Fares, S., Manes, F., Morani, A., Sgrigna, G. & Loreto, F. (2013). Role of biogenic volatile organic compounds (BVOC) emitted by urban trees on ozone concentration in cities: A review. *Environmental Pollution,* **183,** 71-80.

Cameron, R. W. F. & Blanuša, T. (2016). Green infrastructure and ecosystem services – is the devil in the detail? *Annals of Botany,* **118,** 377-391.

Cameron, R. W. F., Blanuša, T., Taylor, J. E., Salisbury, A., Halstead, A. J., Henricot, B. & Thompson, K. (2012). The domestic garden - its contribution to urban green infrastructure. *Urban Forestry and Urban Greening,* **11,** 129-137.

Cameron, R. W. F., Taylor, J. & Emmett, M. (2015). A *Hedera* green façade – Energy performance and saving under different maritime-temperate, winter weather conditions. *Building and Environment,* **92,** 111-121.

Cameron, R. W. F., Taylor, J. E. & Emmett, M. R. (2014). What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls. *Building and Environment,* **73,** 198-207.

Cannell, F. (1998). *Property: Invasion of the climbing plants*. URL: https://www.independent.co.uk/news/business/property-invasion-of-the-climbing-plants-1155873.html: [01/04/2018].

Cantuaria, G. A. C. (2000). A comparative study of the thermal performance of vegetation on building surfaces. In: Steemers, K., Yannas, S. & Organisation, I. P. (eds.) *Architecture, City, Environment: Proceedings of PLEA 2000: July* 2000, *Cambridge.* London: James & James.

Carlos, J. S. (2015). Simulation assessment of living wall thermal performance in winter in the climate of Portugal. *Building Simulation,* **8,** 3-11.

CEEweb. (2016). *Green roof beauty contest 2016*. URL: http://www.ceeweb.org/go-wild/greeen-roof-photo-contest/: [27/05/2018].

Chambers, M. (2018). *Living wall technical irrigation system*. URL: https://www.ansgroupglobal.com/living-wall/technical/irrigation-system: [13/07/2018]

Chapman, P. F. (1975). 4. The energy costs of materials. *Energy Policy,* **3,** 47-57.

Charola, A. E., Grissom, C. A., Erder, E., Wachowiak, M. J. & Oursler, D. (1996). Measuring surface roughness: Three techniques. In: Riederer, J. ed. (1996) *Proceedings of the 8th International Congress on Deterioration and Conservation of Stone.* Berlin, 30th September-4th October 1996. Berlin: Möller Druck und Verlag. pp. 1421-1434.

Chay, K. Y. & Greenstone, M. (2005). Does Air Quality Matter? Evidence from the Housing Market. *Journal of Political Economy,* **113,** 376-424.

Chen, C.-F. (2015). A Preliminary study on carbon sequestration potential of different green roof plants. *International Journal of Research Studies in Biosciences (IJRSB),* **3,** 121-129.

Chen, L., Liu, C., Zhang, L., Zou, R. & Zhang, Z. (2017). Variation in tree species ability to capture and retain airborne fine particulate matter (PM2.5). *Scientific Reports,* **7,** 3206. URL: https://www.nature.com/articles/s41598-017-03360-1: [19/02/2019]

Chiquet, C. (2014). *The animal biodiversity of green walls in the urban environment.* PhD Thesis, Staffordshire University.

Chiquet, C., Dover, J. W. & Mitchell, P. (2013). Birds and the urban environment: The value of green walls. *Urban Ecosystems,* **16,** 453-462.

Cinderby, S., Bagwell, S., DEFRA, Stockholm Environment Institute University of York & London Metropolitan University (2015). *Defra green Victoria evaluation of the Victoria business improvement district (BID) 'Clean and green programme'.* London: DEFRA (Department for Environment, Food and Rural Affairs)

City of Greater Geelong. (2017). *Green roof competition*. URL: https://www.geelongaustralia.com.au /fpg/commercial/article/item/8d4186130a3dccb.aspx: [27/05/2018].

City of London. (2018). *Things to do: Green Spaces*. URL: https://www.cityoflondon.gov.uk/things-to-do/green-spaces/Pages/default.aspx: [31/03/2018].

City of Seattle (2018). *Summary of changes to the stormwater manual.* Seattle, WA: City of Seattle URL: http://www.seattle.gov/Documents/Departments/SDCI/Vault/Stormwater/ SummaryOfChanges.pdf: [20/02/2019]

Clark, J. R. (1983). Age-related changes in trees. *Journal of Arboriculture,* **9,** 201-205.

Claus, K. & Rousseau, S. (2012). Public versus private incentives to invest in green roofs: A cost benefit analysis for Flanders. *Urban Forestry & Urban Greening,* **11,** 417-425.

Community Forests Northwest (2011). *Green infrastructure to combat climate change: A framework for action in Cheshire, Cumbria, Greater Manchester, Lancashire, and Merseyside.* s.l.: Northwest Climate Change Partnership. URL: http://www.greeninfrastructurenw.co.uk/

resources/framework_for_web.pdf: [20/02/2019]

Condron, D. J. (2013). Affluence, inequality, and educational achievement: A structural analysis of 97 jurisdictions across the globe. *Sociological Spectrum,* **33,** 73-97.

Cosgrove, S. (2017). *What role for green walls after Grenfell disaster?* URL: https://www.hortweek.com/role-green-walls-grenfell-disaster/landscape/article/1437460: [10/09/2018].

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V., Paruelo, J., Raskin, R. G., Sutton, P. & van den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature,* **387,** 253-260

CRP (2016). *Green capital: Green infrastructure for a future city.* London: Cross River Partnership. URL: https://crossriverpartnership.org/media/2016/03/CRP-8779-Green-Brochure-AW-WEB-Spreads.pdf: [26/05/2018]

CRP (2018). *Who we are*. URL: https://crossriverpartnership.org/about: [31/07/2018].

Cunningham, C. (2014). *2013 Was a record year for ecoroof construction in Portland, Oregon*. URL: http://www.greenroofs.com/content/articles/118-2013-Was-a-Record-Year-for-Ecoroof-Construction-in-Portland-Oregon.htm: [16/06/2018].

Curran, M. A. (2013). Life cycle assessment: A review of the methodology and its application to sustainability. *Current Opinion in Chemical Engineering,* **2,** 273-277.

D'Ayala, D. & Aktas, Y. D. (2016). Moisture dynamics in the masonry fabric of historic buildings subjected to wind-driven rain and flooding. *Building and Environment,* **104,** 208-220.

Dambreville, A., Griolet, M., Rolland, G., Dauzat, M., Bédiée, A., Balsera, C., Muller, B., Vile, D. & Granier, C. (2016). Phenotyping oilseed rape growth-related traits and their responses to water deficit: The disturbing pot size effect. *Functional Plant Biology,* **44,** 35-45.

Deen, E., Parkhill, M. & Chilton, L. (2016). *Brixton BID Green Infrastructure Audit.* London: LUC (Land Use Consultants). URL: http://www.brixtonbid.co.uk/version2/wp-content/uploads/2016/08/Brixton-BID_GI-Audit-1-1.pdf: [05/04/2018]

Defra (2011). *What are the causes of air pollution.* London: DEFRA. URL: https://uk-air.defra.gov.uk/assets/documents/What_are_the_causes_of_Air_Pollution.pdf: [22/02/2019]

Defra (2015*). Valuing impacts on air quality: Updates in valuing changes in emissions of Oxides of Nitrogen (*NO_X*) and concentrations of Nitrogen Dioxide (*NO_2*).* London: DEFRA. URL: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/460401/air-quality-econanalysis-nitrogen-interim-guidance.pdf: [29/03/2018]

Della Torre, G., Ferranti, F., Lupattelli, M., Pocceschi, N., Figoli, A., Nali, C. & Lorenzini, G. (1998). Effects of ozone on morpho-anatomy and physiology of *Hedera helix*. *Chemosphere,* **36,** 651-656.

Department for Communities and Local Government (2008). *Planning policy statement 12: Creating strong safe and prosperous communities through local spatial planning.* London: TSO (The Stationery Office)

Department for Communities and Local Government. (2011). *External Walls Planning Permission*. URL: http://www.planningportal.gov.uk/permission/commonprojects/externalwalls/: [23/03/2013].

Department for Communities and Local Government (2012). *National planning policy framework*. London: DCLG. URL: https://webarchive.nationalarchives.gov.uk/20180610005038/https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/6077/2116950.pdf: [22/02/2019]

Department of the Environment (2010). Bothered by noise? There's no need to suffer. URL: http://www.doeni.gov.uk/bothered_by_noise_leaflet_-_13_august_2010.pdf: [20/04/2013]

DeWalle, D. R. & Heisler, G. M. (1983). Windbreak effects on air infiltration and space heating in a mobile home. *Energy and Buildings,* **5,** 279-288.

Dhakal, S. (2010). GHG emissions from urbanization and opportunities for urban carbon mitigation. *Current Opinion in Environmental Sustainability,* **2,** 277-283.

Di, H. F. & Wang, D. N. (1999). Cooling effect of ivy on a wall. *Experimental Heat Transfer: A Journal of Thermal Energy Generation, Transport, Storage, and Conversion,* **12,** 235-245.

District of Columbia Municipal Regulations & District of Columbia Register. (2013). *Applicability of green area ratio standards.* Washington D.C.: Office of Documents and Administrative Issuances. URL: https://dcregs.dc.gov/Common/DCMR/SectionList.aspx?SectionId=46197: [13/02/2019].

Djedjig, R., Belarbi, R. & Bozonnet, E. (2017). Experimental study of green walls impacts on buildings in summer and winter under an oceanic climate. *Energy and Buildings,* **150,** 403-411.

Djedjig, R., Bozonnet, E. & Belarbi, R. (2015). Analysis of thermal effects of vegetated envelopes: Integration of a validated model in a building energy simulation program. *Energy and Buildings,* **86,** 93-103.

Dockery, D. W. & Pope, C. A. (1994). Acute respiratory effects of particulate air pollution. *Annual Review of Public Health,* **15,** 107-132.

Doi, Y. (2015). *Nature conservation ordinance is greening Tokyo's buildings*.
URL: https://www.c40.org/case_studies/nature-conservation-ordinance-is-greening-tokyo-s-buildings: [16/06/2018].

Douglas, J. & Noy, E. A. (2011). *Building Surveys and Reports*. 4th ed. Chichester: Wiley-Blackwell.

Dover, J. W. (2015). *Green infrastructure: Incorporating plants and enhancing biodiversity in buildings and urban environments*. Abingdon: Earthscan-Routledge.

DTA Wales (2018). *Welcome to the development trusts association Wales.*
URL: http://www.dtawales.org.uk/: [12/02/2018].

Dunnett, N. & Kingsbury, N. (2008). *Planting green roofs and living walls*. Portland, OR: Timber Press.

EcoMetrix Solutions Group LLC (2014). *Cost analysis for the Portland ecoroof incentive.*
URL: https://www.portlandoregon.gov/Bes/article/522380: [23/02/2019]

ECOTEC Research and Consulting (2008). *The economic benefits of green infrastructure: The public and business case for investing in green infrastructure and a review of the underpinning evidence.* s.l.: Natural Economy Northwest.
URL: https://www.forestry.gov.uk/pdf/nweeconomicbenefitsofgiinvestigating.pdf/$FILE/nweeconomicbenefitsofgiinvestigating.pdf: [23/02/2019]

Environmental Audit Committee (2010). *Air quality fifth report of session 2009–10. Volume 1.* London: TSO (The Stationery Office). URL: https://publications.parliament.uk/pa/cm200910/cmselect/cmenvaud/229/229i.pdf: [23/02/2019]

Enzi, V., Pitha, U., Scharf, B., Oberarzbacher, S., Hancvencl, G. & Wenk, D. (2014). *Leitfaden Fassadenbegrünung* (Façade greening guide).
URL: https://www.wien.gv.at/umweltschutz/raum/pdf/fassadenbegruenung-leitfaden.pdf: [23/02/2019]

EPA. (2017). *Global greenhouse gas emissions data*. URL: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data: [20/04/2018].

EPA. (2018). *Health and environmental effects of particulate matter (PM)*.
URL: https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm: [31/07/2018].

Erbs, D. G., Klein, S. A. & Duffie, J. A. (1982). Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *Solar Energy,* **28,** 293-302.

Ernst, W. H. O. (1996). Phytotoxicity of heavy metals. In: Rodriguez-Barrueco, C. (ed.) *Fertilizers and environment: Proceedings of the International Symposium "Fertilizers and Environment", held in Salamanca, Spain, 26–29, September, 1994.* Dordrecht: Springer Netherlands.

Eumorfopoulou, E. A. & Kontoleon, K. J. (2009). Experimental approach to the contribution of plant-covered walls to the thermal behaviour of building envelopes. *Building and Environment,* **44,** 1024-1038.

Euro Inox (2014). *Roughness measurements of stainless steel surfaces.* URL: http://www.worldstainless.org/Files/issf/non-image-files/PDF/Euro_Inox/Roughness Measurement_EN.pdf: [23/02/2019]

European Commission. (2018). *Investing in green infrastructure*. URL: http://ec.europa.eu/enviro nment/nature/ecosystems/investing/index_en.htm: [23/07/2018].

European Environment Agency (2002). Annex 3: European common indicators: Towards a local sustainability profile. In: *Towards an urban atlas: Assessment of spatial data on 25 European cities and urban areas.* Environmental issue report No. 30/2002. Copenhagen: EEA. URL: https://www.eea.europa.eu/publications/environmental_issue_report_2002_30/chap10-annex3.pdf/view: [23/02/2019]

Fang, C.-F. & Ling, D.-L. (2003). Investigation of the noise reduction provided by tree belts. *Landscape and Urban Planning,* **63,** 187-195.

Federal Interagency Committee for the Management of Noxious and Exotic Weeds & Westbrooks, R. G. (1998). *Invasive plants: Changing the landscape of America* (Paper 490). Logan, UT: US Government Documents (Utah Regional Depository).

Feng, H. & Hewage, K. (2014a). Energy saving performance of green vegetation on LEED certified buildings. *Energy and Buildings,* **75,** 281-289.

Feng, H. & Hewage, K. (2014b). Lifecycle assessment of living walls: air purification and energy performance. *Journal of Cleaner Production,* **69,** 91-99.

Finch, E. (2018). School hedges to trim air pollution. *Islington Tribune*, 27 April, 2018. URL: http://islingtontribune.com/article/school-hedges-to-trim-air-pollution: [23/02/2019]

Finnveden, G. & Ekvall, T. (1998). Life-cycle assessment as a decision-support tool — The case of recycling versus incineration of paper. *Resources, Conservation and Recycling,* **24,** 235-256.

FLL. (2018). *Fassadenbegrünungsrichtlinien – Richtlinien für die Planung, Bau und Instandhaltung von Fassadenbegrünungen* (Façade greening guidelines – Guidelines for the planning, construction and maintenance of facade greening). Bonn: FLL (Forschungsgesellschaft Landschaftsentwickung Landschaftsbau).

Foster, J. S. & Greeno, R. (2013). *Mitchell's Structure & Fabric, Part 1.* 7th ed. Abington: Routledge.

Freer-Smith, P. H., Beckett, K. P. & Taylor, G. (2005). Deposition velocities to *Sorbus aria*, *Acer campestre, Populus deltoides* × trichocarpa 'Beaupré', *Pinus nigra* and × *Cupressocyparis leylandii* for coarse, fine and ultra-fine particles in the urban environment. *Environmental Pollution,* **133,** 157-167.

Fulcher, M. (2009). The Paradise Park fallout: Are living walls worth it? *The Architects' Journal*, 18 September 2009. URL: https://www.architectsjournal.co.uk/home/the-paradise-park-fallout-are-living-walls-worth-it/5208251.article: [23/02/2019]

Gaffin, S. R., Rosenzweig, C., Khanbilvardi, R., Parshall, L., Mahani, S., Glickman, H., Goldberg, R., Blake, R., Slosberg, R. B. & Hillel, D. (2008). Variations in New York city's urban heat island strength over time and space. *Theoretical and Applied Climatology,* **94,** 1-11.

Gallus, J., Kirchner, U., Vogt, R. & Benter, T. (2017). Impact of driving style and road grade on gaseous exhaust emissions of passenger vehicles measured by a portable emission measurement system (PEMS). *Transportation Research Part D: Transport and Environment,* **52,** 215-226.

Garbuzov, M. & Ratnieks, F. L. W. (2014). Ivy: An underappreciated key resource to flower-visiting insects in autumn. *Insect Conservation and Diversity,* **7,** 91-102.

Gaunt, C. (2018). London nurseries to receive air quality audits to combat pollution. *Nursery World*, 24 May 2018. URL: https://www.nurseryworld.co.uk/nursery-world/news/1164565/ london-nurseries-to-receive-air-quality-audits-to-combat-pollution: [23/02/2019]

Geneve, R. L., Hackett, W. P. & Swanson, B. T. (1990). Ethylene production in debladed petioles from the juvenile and mature phases of English ivy in relation to adventitious root initiation. **115,** 123-127.

Gerard, J. (1597). *The herball or generall historie of plantes*. London: John Norton.

Getter, K. L., Rowe, D. B., Robertson, G. P., Cregg, B. M. & Andresen, J. A. (2009). Carbon sequestration potential of extensive green roofs. *Environmental Science & Technology,* **43,** 7564-7570.

Giordano, R., Montacchini, E., Tedesco, S. & Perone, A. (2017). Living wall systems: A technical standard proposal. *Energy Procedia,* **111,** 298-307.

Girouard, R. M. (1967a). Initiation and development of adventitious roots in stem cuttings of *Hedera Helix*: Anatomical studies of the juvenile growth phase. *Canadian Journal of Botany,* **45,** 1877-1881.

Girouard, R. M. (1967b). Initiation and development of adventitious roots in stem cuttings of *Hedera Helix*: Anatomical studies of the mature growth phase. *Canadian Journal of Botany,* **45,** 1883-1886.

Given, D. R. & Meurk, C. (2000). Biodiversity of the urban environment: the importance of indigenous species and the role urban environments can play in their preservation. In: Stewart, G. H. (ed.), *Urban biodiversity and ecology as a basis for holistic planning and design: proceedings of a workshop held at Lincoln University*. Lincoln, New Zealand, 28-29 October 2000. s.l.: Wickliffe Press URL: https://researcharchive.lincoln.ac.nz/bitstream/handle/10182/75/biodiversity.pdf?sequence=1: [23/02/2019]

Givoni, B. (1998). *Climate considerations in building and urban design*. New York, NY: Wiley.

GLA (2009). *Leading to a greener London: An environment programme for the Capital*. London: Greater London Authority.

GLA (2010). Clearing the air: The Mayor's air quality strategy. London: Greater London Authority.

GLA (2011). *The London plan: Spatial development strategy for Greater London*. London: Greater London Authority.

GLA (2012). *Green infrastructure and open Environments: The all London green grid. Supplementary planning guidance, London plan 2011 implementation framework.* London: Greater London Authority.

GLA (2016). *Mayor's air quality fund - Supporting local action on air quality.* London: Greater London Authority.

GLA (2017a). *London Environment Strategy: Draft for Public Consulation.* London: Greater London Authority.

GLA (2017b). *The London plan: The spatial development strategy for Greater London.* London: Greater London Authority.

Godish, T., Davis, W. T. & Fu, J. S. (2014). *Air Quality.* 5th ed. Boca Raton, FL: CRC Press.

Gómez-Baggethun, E. & Barton, D. N. (2013). Classifying and valuing ecosystem services for urban planning. *Ecological Economics,* **86,** 235-245.

Graham, S. (2005). Sustainable building design - a systematic approach. In: Khosrowshahi, F. (ed.), *Proceedings 21st annual ARCOM conference.* London, UK, 7-9 September 2005. Association of Researchers in Construction Management, **1,** 601–10. URL: http://www.arcom.ac.uk/abstracts-browse.php?j=2#2: [23/02/2019]

Grant, G. (2006). *Green roofs and façades*. Bracknell: IHS BRE press

Grant, G. (2012). *Ecosystem services come to town: Greening cities by working with nature*. Chichester: Wiley-Blackwell.

Grant, G., Ward, E. & Gedge, D. (2017). *Urban greening factor for London: Research report.* London: Greater London Authority.

Green, D. W. & Perry, R. H. eds. (2007). *Perry's chemical engineers' handbook.* 8th ed. New York, NY: McGraw-Hill Education.

Green Infrastructure North West (2011). *Building natural value for sustainable economic development: The green infrastructure valuation toolkit user guide.* URL: http://www.greeninfrastructurenw.co.uk/resources/Green_Infrastructure_Valuation_Toolkit_UserGuide.pdf: [23/02/2019]

Greenroofs.com. (2018). *Industry support*.

URL: http://www.greenroofs.com/Greenroofs101/industry_support.htm: [15/02/2018].

Greenway, A. R., Greenwood, S. P., Rhenius, V. J. & Simpson, J. (1975). Unusually severe granulation of winter stores caused by nectar from ivy, *Hedera helix*, in Ireland. *Journal of Apicultural Research*, **14,** 63-68.

Greenway, A. R., Simpson, J. & Smith, M. C. (1978). Granulation of ivy nectar and honey in the honey stomach of the honeybee. *Journal of Apicultural Research*, **17,** 84-88.

Grimmond, S. (2007). Urbanization and global environmental change: Local effects of urban warming. *The Geographical Journal,* **173,** 83-88.

Grissom, C. A., Charola, A. E. & Wachowiak, M. J. (2000). Measuring surface roughness on stone: Back to basics. *Studies in Conservation,* **45,** 73-84.

Groundwork London & Hammersmith & Fulham Council (2016). *Life+ climate-proofing social housing landscapes social return on investment (SROI) report.* London: Groundwork London.

Grundström, M. & Pleijel, H. (2014). Limited effect of urban tree vegetation on NO_2 and O_3 concentrations near a traffic route. *Environmental Pollution,* **189,** 73-76.

Gurr, G. M., Wratten, S. D. & Luna, J. M. (2003). Multi-function agricultural biodiversity: pest management and other benefits. *Basic and Applied Ecology,* **4,** 107-116.

Hall, A. (2010). *Green infrastructure case studies: Municipal policies for managing stormwater with green infrastructure.* Washington, DC: United States Environmental Protection Agency

Hall, J. M., Handley, J. F. & Ennos, A. R. (2012). The potential of tree planting to climate-proof high density residential areas in Manchester, UK. *Landscape and Urban Planning,* **104,** 410-417.

Hamilton, I. G., Steadman, P. J., Bruhns, H., Summerfield, A. J. & Lowe, R. (2013). Energy efficiency in the British housing stock: Energy demand and the Homes Energy Efficiency Database. *Energy Policy,* **60,** 462-480.

Hampton, B. N. (2014). Restoring the Chesapeake Bay and the role of the Maryland rain tax comment. *University of Baltimore Law Forum,* **45,** 198-222.

Harris, M. (2015). *Planning Southampton city centre city centre action plan.* Southampton: Southampton City Council. URL: https://www.southampton.gov.uk/images/ccap-18-march-2015_tcm63-371356.pdf: [12/02/2019].

Hays, R. L. (1975). The thermal conductivity of leaves. *Planta,* **125,** 281-287.

He, J., Hoyano, A. & Asawa, T. (2009). A numerical simulation tool for predicting the impact of outdoor thermal environment on building energy performance. *Applied Energy,* **86,** 1596-1605.

Headley, D. B., Bassuk, N. & Mower, R. G. (1992). Sodium chloride resistance in selected cultivars of *Hedera helix*. *HortScience,* **27,** 249-252.

Hedges Direct. (2018). *Hedges Direct supply to BBC'S The One Show*. URL: http://www.hedgesblog.co.uk/hedges-direct-supply-to-bbcs-the-one-show#.W5pQh_knbIU: [13/09/2018].

Hedlund, H. & Johansson, P. (2000). Heat capacity of birch determined by calorimetry: Implications for the state of water in plants. *Thermochimica Acta,* **349,** 79-88.

Henry, A. & Stewart, J. eds. (2011). *Practical building conservation: Mortars, plasters and renders*. Farnham: Ashgate Publishing.

Herold, A. & McNeil, P. H. (1979). Restoration of photosynthesis in pot-bound tobacco plants. *Journal of Experimental Botany,* **30,** 1187-1194.

Hes, D., Dawkins, A., Jensen, C. & Aye, L. (2011). A modelling method to assess the effect of tree shading for building performance simulation. In: IBPSA. *Building Simulation 2011. 12th Conference of International Building Performance Simulation Association*. Sydney, Australia, 14-16 November 2011. URL:http://ibpsa.org/proceedings/BS2011/P_1176.pdf: [23/02/2019]

Hewitt, C. N. & Street, R. A. (1992). A qualitative assessment of the emission of non-methane hydrocarbon compounds from the biosphere to the atmosphere in the U.K.: Present knowledge and uncertainties. *Atmospheric Environment. Part A. General Topics,* **26,** 3069-3077.

Hibberd, J. S. (1872). *The ivy, a monograph.* London: Groombridge & sons.

Hoelscher, M.-T., Nehls, T., Jänicke, B. & Wessolek, G. (2016). Quantifying cooling effects of façade greening: Shading, transpiration and insulation. *Energy and Buildings,* **114,** 283-290.

Hojati, M., Modarres-Sanavy, S. A. M., Karimi, M. & Ghanati, F. (2011). Responses of growth and antioxidant systems in *Carthamus tinctorius* L. under water deficit stress. *Acta Physiologiae Plantarum,* **33,** 105-112.

Hopkins, G. & Goodwin, C. (2011). *Living architecture: Green roofs and walls*. Collingwood, VIC: CSIRO Publishing.

Horne, R. E., Grant, T. & Verghese, K. (2009). *Life cycle assessment: Principles, practice and prospects*. Collingwood, VIC: CSIRO Publishing.

Horoshenkov, K. V., Khan, A. & Benkreira, H. (2013). Acoustic properties of low growing plants. *The Journal of the Acoustical Society of America,* **133,** 2554-2565.

Howell, J. (2003). *On the level: Plants that drive you up the wall*. URL: https://www.telegraph.co.uk/finance/property/advice/3312221/On-the-level-plants-that-drive-you-up-the-wall.html: [01/04/2018].

Hoyano, A. (1988). Climatological uses of plants for solar control and the effects on the thermal environment of a building. *Energy and Buildings,* **11,** 181-199.

Huang, Y. J., Akbari, H. & Taha, H. (1990). The wind-shielding and shading effects of trees on residential heating and cooling requirements. In: ASHRAE. *1990 Winter ASHRAE Meeting*, Atlanta, GA, 10-14 February 1990. ASHRAE Transactions, **96 (1)**, 1403-1411

Huang, Y. J., Akbari, H., Taha, H. & Rosenfeld, A. H. (1987). The potential of vegetation in reducing summer cooling loads in residential buildings. *Journal of Climate and Applied Meteorology,* **26,** 1103-1116.

Hunt, R. & Franklin, W. (1974). *Resources and environmental profile analysis of nine beverage container alternatives.* Washington, DC: U.S. Environmental Protection Agency (EPA).

Hunter, A. M., Williams, N. S. G., Rayner, J. P., Aye, L., Hes, D. & Livesley, S. J. (2014). Quantifying the thermal performance of green façades: A critical review. *Ecological Engineering,* **63,** 102-113.

Hwang, K. (2016). Cost-benefit analysis: Its usage and critiques. *Journal of Public Affairs,* **16,** 75-80.

IES (2014). *Apache View User Guide <Virtual Environment> 5.9.* URL: http://www.iesve.com/downloads/help/Thermal/ApacheView.pdf: [23/02/2019]

IES (n.d.). *IES <Virtual Environment> Tutorial ModelIT (Version 6.0).* URL: http://www.iesve.com/website/var/assets/training/training_tutorials/modelit_tutorial_ver_6_0_rev1.pdf: [23/02/2019]

IES (2017). *Golden One Center, AECOM*. URL: https://www.iesve.com/software/case-studies/info?building=Golden-One-Center--AECOM&id=6022: [05/10/2017].

IMAP (2013). Growing green guide: Green roofs, walls & facades policy options background paper. URL: http://imap.vic.gov.au/uploads/Growing%20Green%20Guide/Policy%20Options%20Paper%20-%20Green%20Roofs,%20Walls%20and%20Facades.pdf: [23/02/2019]

Ip, K., Lam, M. & Miller, A. (2010). Shading performance of a vertical deciduous climbing plant canopy. *Building and Environment,* **45,** 81-88.

Ip, K., Marta, L. & Miller, A. (2004). Bioshaders for sustainable buildings. In: International Council for Research and Innovation in Building and Construction. *CIB 2004 World Building Congress*, Toronto, Canada, 1-7 May 2004. s.l.: s.n.

Irga, P. J., Braun, J. T., Douglas, A. N. J., Pettit, T., Fujiwara, S., Burchett, M. D. & Torpy, F. R. (2017). The distribution of green walls and green roofs throughout Australia: Do policy instruments influence the frequency of projects? *Urban Forestry & Urban Greening,* **24,** 164-174.

Isaac, M. & van Vuuren, D. P. (2009). Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy,* **37,** 507-521.

Ismail, M. R. & Davies, W. J. (1998). Root restriction affects leaf growth and stomatal response: the role of xylem sap ABA. *Scientia Horticulturae,* **74,** 257-268.

ISO (2006a). *ISO 14040:2006 Environmental management-Life cycle assessment-principles and framework.* Switzerland: International Organization for Standardization. URL: https://www.iso.org/standard/37456.html: [23/02/2019]

ISO (2006b). *ISO 14044:2006 Environmental management-Life cycle assessment-requirements and guidelines.* Switzerland: International Organization for Standardization. URL: https://www.iso.org/standard/38498.html: [23/02/2019]

ISO (2007). *ISO 13370:2007 Thermal performance of buildings - Heat transfer via the ground - Calculation methods.* Switzerland: International Organization for Standardization. URL: https://www.iso.org/standard/40965.html: [25/04/2018]

Jacobs, J. H., Clark, S. J., Denholm, I., Goulson, D., Stoate, C. & Osborne, J. L. (2010). Pollinator effectiveness and fruit set in common ivy, *Hedera helix* (Araliaceae). *Arthropod-Plant Interactions,* **4,** 19-28.

Jacobson, M. Z. (2005). *Fundamentals of atmospheric modeling*. 2nd ed. Cambridge: Cambridge University Press.

Järvelä, E. & Tiihonen, T. (2014). *Developing a green factor tool for the city of Helsinki.* Helsinki: City of Helsinki. URL: https://ilmastotyokalut.fi/files/2014/11/Developing_Helsinki_Green_Factor_Summary_13032014.pdf: [12/02/2019].

Jayalakshmy, M. S. & Philip, J. (2010). Thermophysical properties of plant leaves and their influence on the environment temperature. *International Journal of Thermophysics,* **31,** 2295-2304.

Jones, H. G. (1992). *Plants and microclimate: A quantitative approach to environmental plant physiology*. 2nd ed. Cambridge: Cambridge University Press.

Johnstone, P. (2013). *Planning and managing agricultural and ecological experiments*, Abingdon, Taylor & Francis.

Joye, Y. & De Block, A. (2011). 'Nature and I are two': A critical examination of the biophilia hypothesis. *Environmental Values,* **20,** 189-215.

Kabashima, J. N. (1993). Innovative irrigation techniques in nursery production to reduce water usage. *HortScience,* **28,** 291-293.

Kahn, M. E. (2006). *Green cities: Urban growth and the environment*. Washington, DC: Brookings Institution Press.

Karagiozis, A. N., Salonvaara, M., Holm, A. & Kuenzel, H. (2003). Influence of wind-driven rain data on hygrothermal performance. In: IBPSA. *Building simulation 2003. Proceedings of the eighth international IBPSA conference.* Eindhoven, Netherlands, 11-14 August 2003. URL: http://www.ibpsa.org/proceedings/BS2003/BS03_0627_634.pdf: [23/02/2019]

Karagulian, F., Belis, C. A., Dora, C. F. C., Prüss-Ustün, A. M., Bonjour, S., Adair-Rohani, H. & Amann, M. (2015). Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level. *Atmospheric Environment,* **120,** 475-483.

Kazmierczak, A. & Carter, J. (2010). *Adaptation to climate change using green and blue infrastructure. A database of case studies.* Manchester: University of Manchester p.106. URL: http://orca.cf.ac.uk/64906/1/Database_Final_no_hyperlinks.pdf: [23/02/2019]

Kaźmierczak, A. & Cavan, G. (2011). Surface water flooding risk to urban communities: Analysis of vulnerability, hazard and exposure. *Landscape and Urban Planning,* **103,** 185-197.

Kerr, A. (2012). *Part L conservation of fuel and power*. URL: http://www.calfordseaden.co.uk/news/584/Part-L-Conservation-of-Fuel-and-Power: [23/03/2013]

Kershaw, T., Sanderson, M., Coley, D. & Eames, M. (2010). Estimation of the urban heat island for UK climate change projections. *Building Services Engineering Research and Technology,* **31,** 251-263.

Kerssen, A. J. (2018). *Green roofs and living walls in the Netherlands*. URL: https://livingroofs.org/green-roofs-in-the-netherlands/: [25/05/2018].

Khanna, M. & Anton, W. R. Q. (2002). Corporate environmental management: Regulatory and market-based incentives. *Land Economics,* **78,** 539-558.

Kharkina, T. G., Ottosen, C. O. & Rosenqvist, E. (1999). Effects of root restriction on the growth and physiology of cucumber plants. *Physiologia Plantarum,* **105,** 434-441.

Kimpton, B., Gedge, D. & Grant, G. (2012). London Bridge business improvement district - green infrastructure audit. London: The Ecology Consultancy/The Green Roof Consultancy.

Kirby, A. E. & Kent, A. M. (2010). Architecture as brand: Store design and brand identity. *Journal of Product & Brand Management,* **19,** 432-439.

Kirimtat, A., Koyunbaba, B. K., Chatzikonstantinou, I. & Sariyildiz, S. (2016). Review of simulation modeling for shading devices in buildings. *Renewable and Sustainable Energy Reviews,* **53,** 23-49.

Köhler, M. (1993). *Fassaden- und Dachbegrünung* (Façade and roof greening). Stuttgart: Ulmer Fachbuch.

Köhler, M. (2006). Long-term vegetation research on two extensive green roofs in Berlin. *Urban Habitats,* **4,** 3-26.

Köhler, M. (2008). Green facades—a view back and some visions. *Urban Ecosystems,* **11,** 423-436.

Köhler, M. (2015) *"Green roofs and living walls as tools of Green infrastructure against global warming" Grey–blue-green.* [presentation] (Personal communication, 28/09/2015)

Kolokotroni, M. & Giridharan, R. (2008). Urban heat island intensity in London: An investigation of the impact of physical characteristics on changes in outdoor air temperature during summer. *Solar Energy,* **82,** 986-998.

Kontoleon, K. J. & Eumorfopoulou, E. A. (2010). The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. *Building and Environment,* **45,** 1287-1303.

Kopittke, P. M., Blamey, F. P. C., Asher, C. J. & Menzies, N. W. (2010). Trace metal phytotoxicity in solution culture: a review. *Journal of Experimental Botany,* **61,** 945-954.

Koyama, T., Yoshinaga, M., Hayashi, H., Maeda, K.-i. & Yamauchi, A. (2013). Identification of key plant traits contributing to the cooling effects of green façades using freestanding walls. *Building and Environment,* **66,** 96-103.

Kronvall, J. & Rosenlund, H. (2014). Hygro-thermal and energy related performance of vertical greening on exterior walls – A field measurement study. In: NSB, *10th Nordic Symposium on Building Physics.* Lund, Sweden, 15-19 June 2014. URL: https://www.lunduniversity.lu.se/lup/publication/eadb6ef8-878a-4922-9dbf-384d29ac8b23: [23/02/2019]

Kruuse, A. (2011). *The green space factor and the green points system.* London: Town and Country Planning Association.

Kumaraperumal, K. A. N. (2009). *Modelling and measurement of wind-driven rain on building facades.* PhD Thesis, Glasgow Caledonian University.

Kuo, F. E. & Sullivan, W. C. (2001). Aggression and violence in the inner city effects of environment via mental fatigue. *Environment and Behavior,* **33,** 543-571.

Kuo, W. (2016). *Report of the investigation committee for the CityU sports hall incident.* URL: http://www.cityu.edu.hk/ic/report/CityU_IC_Report.pdf: [23/02/2019]

LaClergue, D. (ca. 2014) *Seattle green factor: Improving livability and ecological function through landscaping standards.* Seattle, WA: City of Seattle. URL:https://www.seattle.gov/util/cs/groups/public/@spu/@conservation/documents/webcontent/01_027984.pdf: [11/02/2019].

Landscape Institute (2013). *Green infrastructure: An integrated approach to land use.* London: Landscape Institute.

Landschaft Planen & Bauen & Richard, B. G. M. (1990). *The biotope area factor as an ecological parameter - excerpt.* URL: https://www.berlin.de/senuvk/umwelt/landschaftsplanung/bff/download/Auszug_BFF_Gutachten_1990_eng.pdf: [23/02/2019]

Langdon, D. ed. (2014). *Spon's external works and landscape price*. 33rd ed. Boca Raton: CRC Press.

Laparé, F. (2013). *The green room method: Incorporating green façades into whole building energy models.* Master of Building Science Major Research Project, Ryerson University.

Larsen, S. F., Filippín, C. & Lesino, G. (2014). Thermal simulation of a double skin façade with plants. *Energy Procedia,* **57,** 1763-1772.

Larsen, S. F., Filippín, C. & Lesino, G. (2015). Modeling double skin green façades with traditional thermal simulation software. *Solar Energy,* **121,** 56-67.

Laussmann, D. & Helm, D. (2011). Air change measurements using tracer gases. In: Mazzeo, N. ed. (2011) *Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality*. s.l.: IntechOpen. pp 365-406. URL: https://www.intechopen.com/books/chemistry-emission-control-radioactive-pollution-and-indoor-air-quality: [24/02/2019]

Laville, S. (2017). *Air pollution kills more people in the UK than in Sweden, US and Mexico* URL: https://www.theguardian.com/environment/2017/may/17/air-pollution-kills-more-people-in-the-uk-than-in-sweden-us-and-mexico: [12/07/2018].

Lazzerini, G., Lucchetti, S. & Nicese, F. P. (2016). Green house gases (GHG) emissions from the ornamental plant nursery industry: A life cycle assessment (LCA) approach in a nursery district in central Italy. *Journal of Cleaner Production,* **112,** 4022-4030.

Lee, H.-J., Kim, S.-Y. & Yun, C.-Y. (2017). Comparison of solar radiation models to estimate direct normal irradiance for Korea. *Energies,* **10,** 594 (Article number 594). URL: https://www.mdpi.com/1996-1073/10/5/594: [24/02/2019]

Lemos, A. L. B. F. & Kauškale, L. (2017). Factors influencing green roof development in Recife, Brazil. *Baltic Journal of Real Estate Economics and Construction Management*, **5,** 146-159.

Lenaghan, S. C. & Zhang, M. (2012). Real-time observation of the secretion of a nanocomposite adhesive from English ivy (*Hedera helix*). *Plant Science : An International Journal of Experimental Plant Biology,* **183,** 206-11.

Leonard, R. J., McArthur, C. & Hochuli, D. F. (2016). Particulate matter deposition on roadside plants and the importance of leaf trait combinations. *Urban Forestry & Urban Greening,* **20,** 249-253.

Lim, M. (2009). UK building energy calculation software approval scheme. In: IBPSA, *Proceedings of the Eleventh International IBPSA Conference (Building Simulation '09)*. Glasgow, Scotland, 27-30 July 2009. URL: http://www.ibpsa.org/proceedings/BS2009/BS09_0553_560.pdf: [24/02/2019]

Liu, H., Gao, L., Shang, Q. & Xiao, G. (2013). Preparation and characterization of polyurethane clearcoats and investigation into their antigraffiti property. *Journal of Coatings Technology and Research*, **10,** 775-784.

Liu, N., Lin, Z. & Mo, H. (2012). Metal (Pb, Cd, and Cu)-induced reactive oxygen species accumulations in aerial root cells of the Chinese banyan (*Ficus microcarpa*). *Ecotoxicology,* **21,** 2004-2011.

Liu, Y. & Harris, D. J. (2008). Effects of shelterbelt trees on reducing heating-energy consumption of office buildings in Scotland. *Applied Energy,* **85,** 115-127.

Lombardi, D. R., Leach, J. M., Rogers, C. D. F. & The Urban Futures Team (2012). *Designing resilient cities: A guide to good practice*. Bracknell: IHS BRE Press.

Lyons, A. (2010). *Materials for Architects and Builders*. Oxford: Taylor & Francis.

Lyytimäki, J. & Sipilä, M. (2009). Hopping on one leg – The challenge of ecosystem disservices for urban green management. *Urban Forestry & Urban Greening,* **8,** 309-315.

M&S (Marks and Spencer) (2017). *Plan A Report.* URL: http://planareport.marksandspencer.com/M&S_PlanAReport_2017_FullReport.pdf: [19/05/2019]

Madre, F., Clergeau, P., Machon, N. & Vergnes, A. (2015). Building biodiversity: Vegetated façades as habitats for spider and beetle assemblages. *Global Ecology and Conservation,* **3,** 222-233.

Maloney, R. (2016). *WeatherShift™ future weather data now available for online purchase*. URL: https://www.arup.com/news-and-events/news/weathershift-future-weather-data-now-available-for-online-purchase: [09/12/2017].

Malys, L., Musy, M. & Inard, C. (2014). A hydrothermal model to assess the impact of green walls on urban microclimate and building energy consumption. *Building and Environment,* **73,** 187-197.

Manco, J. (2009). *History of building regulations in the British Isles.* URL: http://www.buildinghistory.org/regulations.shtml: [22/01/2019]

Mangone, G. & van der Linden, K. (2014). Forest microclimates: Investigating the performance potential of vegetation at the building space scale. *Building and Environment,* **73,** 12-23.

Manso, M. & Castro-Gomes, J. (2015). Green wall systems: A review of their characteristics. *Renewable and Sustainable Energy Reviews,* **41,** 863-871.

Marchi, M., Pulselli, R. M., Marchettini, N., Pulselli, F. M. & Bastianoni, S. (2015). Carbon dioxide sequestration model of a vertical greenery system. *Ecological Modelling,* **306,** 46-56.

Marshall, D. & Dann, N. (2005). *House Inspector*. Abingdon: EG Books.

Matheus, C., Caetano, F. D. N., Morelli, D. D. d. O. & Labaki, L. C. (2016). Desempenho térmico de envoltórias vegetadas em edificações no sudeste brasileiro (Thermal performance of vegetated envelopes in buildings in southeastern Brazil). *Ambiente Construído,* **16,** 71-81.

Matt, S. (2012). *Green façades provide habitat for arthropods on buildings in the Washington, DC metro area.* Master of Science Thesis, University of Maryland, College Park.

McAllister, H. & Marshall, R. (2017). *Hedera: the complete guide.* London: Royal Horticultural Society (RHS).

McAllister, H. A. & Rutherford, A. (1990). *Hedera helix* L. and *H. hibernica* (Kirchner) Bean (*Araliaceae*) in the British Isles. *Watsonia,* **18,** 7-15.

McIntosh, A. (2010). Green roofs in Seattle: A survey of vegetated roofs and rooftop gardens. Seattle: City of Seattle. URL: https://www.seattle.gov/Documents/Departments/OSE/Green-Roofs-In-Seattle.pdf: [25/02/2019]

McKay, W. B. (2015). *McKay's building construction*. Abingdon: Routledge.

McPherson, E. G., Herrington, L. P. & Heisler, G. M. (1988). Impacts of vegetation on residential heating and cooling. *Energy and Buildings,* **12,** 41-51.

Melzer, B., Seidel, R., Steinbrecher, T. & Speck, T. (2012). Structure, attachment properties, and ecological importance of the attachment system of English ivy (*Hedera helix*). *Journal of experimental botany,* **63,** 191-201.

Melzer, B., Steinbrecher, T., Seidel, R., Kraft, O., Schwaiger, R. & Speck, T. (2010). The attachment strategy of English ivy: A complex mechanism acting on several hierarchical levels. *Journal of the Royal Society Interface,* **7,** 1383-9.

Melzer, B., Steinbrecher, T., Seidel, R., Kraft, O. & Speck, T. (2009). Mechanics and structure of the attachment system of English ivy (*Hedera helix* L .). In: *6th Plant Biomechanics Conference*, Cayenne, French Guiana, 16-21 November 2009. URL: http://www.iap.tuwien.ac.at/~gebeshuber/Proceedings_PBM_2009.pdf: pp. 205-210. [25/02/2019]

Merk, O., Saussier, S., Staropoli, C., Slack, E. & Kim, J.-H. (2012). *Financing green urban infrastructure.* OECD Regional Development Working Papers, No. 2012/10. Paris: OECD Publishing. URL: https://doi.org/10.1787/5k92p0c6j6r0-en: [25/02/2019]

Metcalfe, D. J. (2005). *Hedera helix* L. *Journal of Ecology,* **93,** 632-648.

Miller, A., Shaw, K. & Lam, M. (2007). *Case study report - Vegetation on building facades: "Bioshader"*. Brighton: University of Brighton.

Ministry of Housing Communities & Local Government (2014). *DCLG approved national calculation methodologies and software programs for buildings other than dwellings.* London: DCLG.

Ministry of Land, Infrastructure, Transport, and Tourism (2014). 新たな屋上・壁面緑化空間が創出されていますー 平成25年全国屋上･壁面緑化施工実績調査について. (New green roofs/walls - Survey on the results of rooftop and wall greening construction nationwide in Heisei 20). URL: http://www.mlit.go.jp/common/001053622.pdf: [25/02/2019]

Mobilane UK Ltd. (2018a). *Green Screens bring "cleaner, safer air" to South East London school*. URL: https://mobilane.co.uk/case-studies/green-screens-cleaner-safer-air-london-school/: [21/05/2018].

Mobilane UK Ltd. (2018b). *Instant Green Screen, grown by Mobilane*. URL: https://mobilane.co.uk/products/green-screen/: [12/05/2018].

Mobilane UK Ltd. (2018c). *Projects*. URL: https://mobilane.co.uk/projects/: [23/03/2018].

Moore, G. A. (2014). *Crossing the Chasm: Marketing and Selling Disruptive Products to Mainstream Customers*. 3rd ed. New York, NY: HarperCollins.

Morel, J. L., Schwartz, C., Florentin, L. & de Kimpe, C. (2005). Urban soils. In: Hillel, D. (ed.) *Encyclopedia of soils in the environment.* Oxford: Elsevier.

Muckley, W. J. (1886). Ivy a cure for damp walls. *The Garden: An Illustrated Weekly Journal of Horticulture in All Its Branches.* **29,** 163 (column 2). URL: https://www.biodiversitylibrary.org/item/82670#page/193/mode/1up: [25/02/2019]

Mundy, J. (2015). *The green guide explained.* Watford: BRE. URL: https://www.bre.co.uk/filelibrary /greenguide/PDF/The-Green-Guide-Explained_March2015.pdf: [25/02/2019]

Musy, M., Malys, L., Morille, B. & Inard, C. (2015). The use of SOLENE-microclimat model to assess adaptation strategies at the district scale. *Urban Climate,* **14,** 213-223.

Natarajan, M., Rahimi, M., Sen, S., Mackenzie, N. & Imanbayev, Y. (2015). Living wall systems: Evaluating life-cycle energy, water and carbon impacts. *Urban Ecosystems,* **18,** 1-11.

Natural Economy Northwest (2009). *Natural benefits for business*. URL: http://www.gmbp.org.uk/ site/images/stories/natural_benefits_for_business_-_case_studies%5b1%5d.pdf: [25/02/2019]

Natural Economy Northwest (2010). *A future for the natural economy: The achievements and legacy of the Natural Economy Northwest partnership.* s.l.: NENW

Natural England (2009). *NE220: No charge? Valuing the natural environment.* URL: http://publications.naturalengland.org.uk/publication/36019: [25/02/2019]

Natural England (2013a). *NECR126: Green infrastructure–valuation tools assessment.* URL: http://publications.naturalengland.org.uk/publication/6264318517575680: [30/03/2018]

Natural England (2013b). *Greening for growth in Victoria: Green infrastructure case study.* URL: http://publications.naturalengland.org.uk/publication/11844873: [31/03/2018]

Natural England (2015). *Natural England access to evidence information note EIN009 - Summary of evidence: Land use.* URL: http://publications.naturalengland.org.uk/file/5874576670064640: [25/02/2019]

Negbi, M., Zamski, E. & Ze'Evi, O. (1982). Photo- and thigmomorphogenetic control of the attachment of the ivy (*Hedera helix* L.) to its support. *Zeitschrift für Pflanzenphysiologie,* **108,** 9-15.

NeSmith, D. S. & Duval, J. R. (1998). The effect of container size. *HortTechnology,* **8,** 495-498.

Ng, E., Chen, L., Wang, Y. & Yuan, C. (2012). A study on the cooling effects of greening in a high-density city: An experience from Hong Kong. *Building and Environment,* **47,** 256-271.

Ngan, G. (2004). *Green roof policies: Tools for encouraging sustainable design.* URL: https://www.coolrooftoolkit.org/wp-content/uploads/2012/04/Green-Roof-Policy-report-Goya-Ngan.pdf: [25/02/2019]

Nicholson, A. L., Olivetti, E. A., Gregory, J. R., Field, F. R. & Kirchain, R. E. (2009). End-of-life LCA allocation methods: Open loop recycling impacts on robustness of material selection decisions. In: IEEE (Institute of Electrical and Electronics Engineers), 2009 IEEE International Symposium on Sustainable Systems and Technology, 18-20 May 2009, Phoenix, AZ. URL: https://ieeexplore.ieee.org/document/5156769: [25/02/2019]

Nickel, D., Schoenfelder, W., Medearis, D., Dolowitz, D. P., Keeley, M. & Shuster, W. (2014). German experience in managing stormwater with green infrastructure. *Journal of Environmental Planning and Management,* **57,** 403-423.

Niinemets, Ü. & Peñuelas, J. (2008). Gardening and urban landscaping: Significant players in global change. *Trends in Plant Science,* **13,** 60-65

Nikoofard, S., Ugursal, V. I. & Beausoleil-Morrison, I. (2011). Effect of external shading on household energy requirement for heating and cooling in Canada. *Energy and Buildings,* **43,** 1627-1635.

Noble, A. G. (1980). Noise Pollution In Selected Chinese and American Cities. *GeoJournal,* **4,** 573-575.

Noble, A. G. (2007). *Traditional buildings: A global survey of structural forms and cultural functions*. London: I. B. Tauris.

Nolan, P. (2017). *Green infrastructure action plan background Liverpool City central and commercial district business improvement districts*. Warrington: The Mersey Forest.

NRC (National Research Council) (1991) *Rethinking the ozone problem in urban and regional air pollution*. Washington, DC: The National Academies Press.
URL: https://doi.org/10.17226/1889: [22/03/2019]

O'Malley, C., Piroozfar, P., Farr, E. R. P. & Pomponi, F. (2015). Urban heat island (UHI) mitigating strategies: A case-based comparative analysis. *Sustainable Cities and Society,* **19,** 222-235.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R. R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K. K. Y. & Rowe, B. (2007). Green roofs as urban ecosystems: Ecological structures, functions, and services. *BioScience,* **57,** 823-833.

Ofgem (2017). *Energy company obligation - Percentage of property treated (POPT) review.* London: Ofgem

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society,* **108,** 1-24.

Olivieri, F., Grifoni, R. C., Redondas, D., Sánchez-Reséndiz, J. A. & Tascini, S. (2017). An experimental method to quantitatively analyse the effect of thermal insulation thickness on the summer performance of a vertical green wall. *Energy and Buildings,* **150,** 132-148.

ONS (Office for National Statistics) (2011). *2011 Census: Characteristics of Built-Up Areas*. URL: https://www.ons.gov.uk/peoplepopulationandcommunity/housing/articles/characteristicsofbuiltupareas/2013-06-28: [16/06/2018]

Osório, J., Osório, M. L., Chaves, M. M. & Pereira, J. S. (1998). Water deficits are more important in delaying growth than in changing patterns of carbon allocation in *Eucalyptus globulus*. *Tree Physiology,* **18,** 363-373.

Ottelé, M. (2011). *The Green Building Envelope Vertical Greening.* PhD Thesis, Technische Universiteit Delft, Netherlands

Ottelé, M. & Perini, K. (2017). Comparative experimental approach to investigate the thermal behaviour of vertical greened façades of buildings. *Ecological Engineering,* **108,** 152-161.

Ottelé, M., Perini, K., Fraaij, A. L. A., Haas, E. M. & Raiteri, R. (2011). Comparative life cycle analysis for green façades and living wall systems. *Energy and Buildings,* **43,** 3419-3429.

Ottelé, M., van Bohemen, H. D. & Fraaij, A. L. A. (2010). Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecological Engineering,* **36,** 154-162.

Owens, J. W. (1997). Life-cycle assessment: Constraints on moving from inventory to impact assessment. *Journal of Industrial Ecology,* **1,** 37-49.

Page, J. (2003). The role of solar radiation climatology in the design of PV systems. In: Markvart, T. & Castañer, L. (eds.) *Practical handbook of photovoltaics: Fundamentals and applications.* Oxford: Elsevier Science. pp. 5-70

Pan, L. & Chu, L. M. (2016). Energy saving potential and life cycle environmental impacts of a vertical greenery system in Hong Kong: A case study. *Building and Environment,* **96,** 293-300.

Pan, X. C. & Xiao, Y. X. (2014). Simulation analysis of building green facade eco-effect. *Applied Mechanics and Materials*, **548,** 1701-1705.

Papadakis, G., Tsamis, P. & Kyritsis, S. (2001). An experimental investigation of the effect of shading with plants for solar control of buildings. *Energy and Buildings,* **33,** 831-836.

Park, J. (2015). *One hundred years of housing space standards: What now?* URL: http://housingspacestandards.co.uk/assets/space-standards_onscreen.pdf: [26/02/2019]

Paulsen, E., Christensen, L. P. & Andersen, K. E. (2010). Dermatitis from common ivy (*Hedera helix* L. subsp. helix) in Europe: past, present, and future. *Contact Dermatitis,* **62,** 201-209.

Peck, S. W., Callaghan, C., Kuhn, M. E. & Bass, B. (1999). *Greenbacks from green roofs : Forging a new industry in Canada: Status report on benefits, barriers and opportunities for green roof and vertical garden technology diffusion.* Ottawa: Canada Mortgage and Housing Corporation.

Peel, K. (2017). Plants are our best defence against air pollution. *The Sunday Times*, (Last updated 12:01am on 16 July 2017). URL: https://www.thetimes.co.uk/article/plants-are-our-best-defence-against-air-pollution-t7t3hmtpw: [26/02/2019]

Pekkanen, J., Peters, A., Hoek, G., Tiittanen, P., Brunekreef, B., de Hartog, J., Heinrich, J., Ibald-Mulli, A., Kreyling, W. G., Lanki, T., Timonen, K. L. & Vanninen, E. (2002). Particulate air pollution and risk of ST-Segment depression during repeated submaximal exercise tests among subjects with coronary heart disease: The exposure and risk assessment for fine and ultrafine particles in ambient air (ULTRA) study. *Circulation,* **106,** 933-938.

Pengelly Consulting (2010). 'Nature Nearby' accessible natural greenspace guidance. URL: http://publications.naturalengland.org.uk/publication/40004?category=47004:[23/03/2013]

Percival, G. C. (2005). Identification of foliar salt tolerance of woody perennials using chlorophyll fluorescence. *HortScience,* **40,** 1892-1897.

Pérez, G., Coma, J., Martorell, I. & Cabeza, L. F. (2014). Vertical greenery systems (VGS) for energy saving in buildings: A review. *Renewable and Sustainable Energy Reviews,* **39,** 139-165.

Pérez, G., Rincón, L., Vila, A., González, J. M. & Cabeza, L. F. (2011a). Behaviour of green facades in Mediterranean continental climate. *Energy Conversion and Management,* **52,** 1861-1867.

Pérez, G., Rincón, L., Vila, A., González, J. M. & Cabeza, L. F. (2011b). Green vertical systems for buildings as passive systems for energy savings. *Applied Energy,* **88,** 4854-4859.

Perini, K. (2013). Retrofitting with vegetation recent building heritage applying a design tool—the case study of a school building. *Frontiers of Architectural Research,* **2,** 267-277.

Perini, K., Magliocco, A. & Giulini, S. (2017a). Vertical greening systems evaporation measurements: Does plant species influence cooling performances? *International Journal of Ventilation,* **16,** 152-160.

Perini, K., Ottelé, M., Fraaij, A. L. A., Haas, E. M. & Raiteri, R. (2011a). Vertical greening systems and the effect on air flow and temperature on the building envelope. *Building and Environment,* **46,** 2287-2294.

Perini, K., Ottelé, M., Giulini, S., Magliocco, A. & Roccotiello, E. (2017b). Quantification of fine dust deposition on different plant species in a vertical greening system. *Ecological Engineering,* **100,** 268-276.

Perini, K., Ottelé, M., Haas, E. M. & Raiteri, R. (2011b). Greening the building envelope, façade greening and living wall systems. *Open Journal of Ecology,* **01,** 1-8.

Perini, K. & Rosasco, P. (2013). Cost–benefit analysis for green façades and living wall systems. *Building and Environment,* **70,** 110-121.

Peterson, T. A., Reinsel, M. D. & Krizek, D. T. (1991). Tomato (*Lycopersicon esculentum* Mill., cv. 'Better Bush') plant response to root restriction I. Alteration of plant morphology. *Journal of Experimental Botany,* **42,** 1233-1240.

Plant Connection Inc. (2018). *Green Roof Legislation, Policies & Tax Incentives*. URL: http://myplantconnection.com/green-roofs-legislation.php: [15/02/2018].

Pomponi, F. & D'Amico, B. (2017). Holistic study of a timber double skin façade: Whole life carbon emissions and structural optimisation. *Building and Environment,* **124,** 42-56.

Poorter, H., Bühler, J., van Dusschoten, D., Climent, J. & Postma, J. A. (2012). Pot size matters: A meta-analysis of the effects of rooting volume on plant growth. *Functional Plant Biology,* **39,** 839-850.

Pretty, J., Peacock, J., Sellens, M. & Griffin, M. (2005). The mental and physical health outcomes of green exercise. *International Journal of Environmental Health Research,* **15,** 319-337.

Progrss. (2016). *Argentinian bylaw requires green roofs in Cordoba*. URL: https://progrss.com/sustainability/20160718/argentinian-bylaw-requires-green-roofs-in-cordoba/: [15/02/2018].

Pugh, T. A., Mackenzie, A. R., Whyatt, J. D. & Hewitt, C. N. (2012). Effectiveness of green infrastructure for improvement of air quality in urban street canyons. *Environmental Science & Technology,* **46,** 7692-7699.

Ranade, A., Kersh, K. & Raje, J. (2012). *Building-integrated vegetation: Redefining the landscape or chasing a mirage?* Boston: Lux research.

Rath, J., Kießl, K. & Gertis, K. (1989). *Auswirkungen von Fassadenbegrünungen auf den Wärme- und Feuchtehaushalt von Außenwänden und Schadensrisiko* (Effects of facade greening on the heat and moisture balance of exterior walls and damage risk). Stuttgart: Fraunhofer IRB-Verlag.

Ray, J. D. & Sinclair, T. R. (1998). The effect of pot size on growth and transpiration of maize and soybean during water deficit stress. *Journal of Experimental Botany,* **49,** 1381-1386.

Reap, J., Roman, F., Duncan, S. & Bras, B. (2008a). A survey of unresolved problems in life cycle assessment: Part 1 Goal and scope and inventory analysis. *The International Journal of Life Cycle Assessment,* **13,** 290-300.

Reap, J., Roman, F., Duncan, S. & Bras, B. (2008b). A survey of unresolved problems in life cycle assessment Part 2: Impact assessment and interpretation. *The International Journal of Life Cycle Assessment,* **13,** 374-388.

Reineke, R. A., Hackett, W. P. & Smith, A. G. (2002). Lignification associated with decreased adventitious rooting competence of English ivy petioles. *Journal of Environmental Horticulture,* **20,** 236–239.

Richards, D. & Rowe, R. N. (1977). Effects of root restriction, root pruning and 6-benzylaminopurine on the growth of peach seedlings. *Annals of botany,* **41,** 729-740.

Ridge, R. & Katsumi, M. (2002). Root hairs: Hormones and tip molecules. In: Waisel, Y., Eshel, A., Beeckman, T. & Kafkafi, U. (eds.) *Plant Roots, the hidden half.* 3rd ed. Boca Raton, FL: CRC Press. pp. 83-91

Rogers, P. L. (2000). Barriers to adopting emerging technologies in education. *Journal of Educational Computing Research,* **22,** 455-472.

Rose, P. Q. (1980). *Ivies*. Poole: Blandford Press.

Rose, P. Q. (1996). *The gardener's guide to growing ivies*. Portland, OR: Timber Press.

Ross, K. (2002). *Non-traditional housing in the UK - a brief review.* Building Research Establishment (BRE) for the Council of Mortgage Lenders, London

Rothamsted Experimental Station (1975). *Report*. Harpenden: Lawes Agricultural Trust. p. 114.

Rowe, D. B. (2011). Green roofs as a means of pollution abatement. *Environmental Pollution,* **159,** 2100-2110.

Royal College of Physicians (2016). *Every breath we take: the lifelong impact of air pollution. Report of a working party.* London: Royal College of Physicians.

Royal Horticultural Society. (2018a). *Find a plant*. URL: https://www.rhs.org.uk/plants/search-form: [12/05/2018].

Royal Horticultural Society. (2018b). *Hedges: nuisance and overgrown*.
URL: https://www.rhs.org.uk/advice/profile?PID=408: [10/05/2018].

Royal Horticultural Society. (2018c). *Trees and the law*.
URL: https://www.rhs.org.uk/advice/profile?PID=1022: [10/05/2018].

Russo, G. & De Lucia Zeller, B. (2008). Environmental evaluation by means of LCA regarding the ornamental nursery production in rose and sowbread greenhouse cultivation. *Acta Horticulturae,* **801,** 1597-1604.

Ryokka. (2008). *緑化スタイル・屋上緑化に関する条例* (Greenroof laws)
URL: http://www.ryokka.org/info/regulation/: [16/06/2018].

Sæbø, A., Popek, R., Nawrot, B., Hanslin, H. M., Gawronska, H. & Gawronski, S. W. (2012). Plant species differences in particulate matter accumulation on leaf surfaces. *Science of The Total Environment,* **427-428,** 347-354.

Santamouris, M. (2014). On the energy impact of urban heat island and global warming on buildings. *Energy and Buildings,* **82,** 100-113.

Saul, G. H. (1968). Copper safely controls roots of tubed seedlings. *Tree Planters Notes,* **19 (1),** 7-9.

Sauter, A., Hose, E. & Hartung, W. (2002). Abscisic acid in roots-biochemistry and physiology. In: Waisel, Y., Eshel, A., Beeckman, T. & Kafkafi, U. (eds.) *Plant Roots, the hidden half.* 3rd ed. Boca Raton, FL: CRC Press. pp. 435-448.

Scarpa, M., Mazzali, U. & Peron, F. (2014). Modeling the energy performance of living walls: Validation against field measurements in temperate climate. *Energy and Buildings,* **79,** 155-163.

Schulze, E.-D., Kelliher, F. M., Körner, C., Lloyd, J. & Leuning, R. (1994). Relationships among maximum stomatal conductance, ecosystem surface conductance, carbon assimilation rate, and plant nitrogen nutrition: A global ecology scaling exercise. *Annual Review of Ecology and Systematics*, **25,** 629-660.

Schwartz, T. A. ed. (1991). *Water in exterior building walls: Problems and solutions*. Philadelphia, PA: ASTM.

Scotscape. (2018). *Living walls case studies*. URL: https://www.scotscape.net/living-walls-case-studies/: [24/03/2018].

Segerson, K. (1999). Mandatory versus voluntary approaches to food safety. *Agribusiness,* **15,** 53-70.

Senapathi, D., Biesmeijer, J. C., Breeze, T. D., Kleijn, D., Potts, S. G. & Carvalheiro, L. G. (2015). Pollinator conservation—the difference between managing for pollination services and preserving pollinator diversity. *Current Opinion in Insect Science,* **12,** 93-101.

Senatsverwaltung für Umwelt Verkehr und Klimaschutz. (2018). *Grüne Innenstadt - BFF - Biotopflächen-faktor* (Green city center - BFF - biotope area factor). URL: https://www.berlin.de/senuvk/umwelt/landschaftsplanung/bff/index.shtml: [01/04/2018].

Setälä, H., Viippola, V., Rantalainen, A.-L., Pennanen, A. & Yli-Pelkonen, V. (2013). Does urban vegetation mitigate air pollution in northern conditions? *Environmental Pollution,* **183,** 104-112.

Shackleton, K., Bell, N., Smith, H. & Davies, L. (2012). *The role of shrubs and perennials in the capture and mitigation of particulate air pollution in London.* London: Centre for Environmental Policy, Imperial College London.

Sharp, R. E., Poroyko, V., Hejlek, L. G., Spollen, W. G., Springer, G. K., Bohnert, H. J. & Nguyen, H. T. (2004). Root growth maintenance during water deficits: physiology to functional genomics. *Journal of Experimental Botany,* **55,** 2343-2351.

Simpson, J. R. (2002). Improved estimates of tree-shade effects on residential energy use. *Energy and Buildings,* **34,** 1067-1076.

Simpson, S., Banfill, P., Haines, V., Mallaband, B. & Mitchell, V. (2016). Energy-led domestic retrofit: Impact of the intervention sequence. *Building Research & Information,* **44,** 97-115.

Skelhorn, C., Lindley, S. & Levermore, G. (2014). The impact of vegetation types on air and surface temperatures in a temperate city: A fine scale assessment in Manchester, UK. *Landscape and Urban Planning,* **121,** 129-140.

Skelhorn, C. P., Levermore, G. & Lindley, S. J. (2016). Impacts on cooling energy consumption due to the UHI and vegetation changes in Manchester, UK. *Energy and Buildings,* **122,** 150-159.

Southampton City Council (2015). *Southampton City Council Green Space Factor Guidance Notes.* Southampton: Southampton City Council. URL: https://www.southampton.gov.uk/policies/green-space-factor-guidance-notes-2015_tcm63-371696.pdf: [27/02/2019]

Speak, A. F., Rothwell, J. J., Lindley, S. J. & Smith, C. L. (2012). Urban particulate pollution reduction by four species of green roof vegetation in a UK city. *Atmospheric Environment,* **61,** 283-293.

Stafford, S. L. (2011). How green is your campus? An analysis of the factors that drive universities to embrace sustainability. *Contemporary Economic Policy,* **29,** 337-356.

State of Michigan Legislative Council (2017). *Principal Shopping Districts and Business Improvement Districts Act 120 of 1961*. URL: http://www.legislature.mi.gov/(S(3edraxzj0o5hxsl5fhno4xri))/mileg.aspx?page=getobject&objectname=mcl-act-120-of-1961: [31/07/2018].

Steinbrecher, T., Danninger, E., Harder, D., Speck, T., Kraft, O. & Schwaiger, R. (2010). Quantifying the attachment strength of climbing plants: A new approach. *Acta Biomaterialia,* **6,** 1497-1504.

Sternberg, T., Ashbee, J., Cathersides, A., Thomas, R., Turner, C., Viles, H. & White, A. (2010a). *Ivy on walls: Seminar report.* s.l.: English Heritage. URL: https://www.geog.ox.ac.uk/research/landscape/rubble/ivy/ivy-report.pdf: [27/02/2019]

Sternberg, T., Viles, H. & Cathersides, A. (2011a). Evaluating the role of ivy (*Hedera helix*) in moderating wall surface microclimates and contributing to the bioprotection of historic buildings. *Building and Environment,* **46,** 293-297.

Sternberg, T., Viles, H., Cathersides, A. & Edwards, M. (2010b). Dust particulate absorption by ivy (*Hedera helix* L) on historic walls in urban environments. *Science of The Total Environment,* **409,** 162-168.

Sternberg, T., Viles, H. & Edwards, M. (2011b). Notice of retraction: Absorption of airborne particulates and pollutants by ivy (*Hedera helix* L) in Oxford, UK. In: IEEE. *5th International Conference on Bioinformatics and Biomedical Engineering*. Wuhan, China, 10-12 May 2011. URL: https://ieeexplore.ieee.org/document/5781298: [27/02/2019]

Steubing, L., Fangmeier, A., Both, R. & Frankenfeld, M. (1989). Effects of SO_2, NO_2, and O_3 on population development and morphological and physiological parameters of native herb layer species in a beech forest. *Environmental Pollution,* **58,** 281-302.

Stevenson, C. A. & Laidlaw, A. S. (1985). The effect of moisture stress on stolon and adventitious root development in white clover (*Trifolium repens* L.). *Plant and Soil,* **85,** 249-257.

Straube, J. F. (1999). *Moisture control and enclosure wall systems.* PhD Thesis, University of Waterloo.

Struve, D. K. & Rhodus, T. (1990). Turning copper into gold. *American Nurseryman,* **172,** 114-125.

Sundquist, K., Frank, G. & Sundquist, J. (2004). Urbanisation and incidence of psychosis and depression: Follow-up study of 4.4 million women and men in Sweden. *The British Journal of Psychiatry,* **184,** 293-298.

Susorova, I., Angulo, M., Bahrami, P. & Brent, S. (2013). A model of vegetated exterior facades for evaluation of wall thermal performance. *Building and Environment,* **67,** 1-13.

Swindon Borough Council (2005). *Noise nuisance advice pack*. Swindon: Swindon Borough Council URL: http://www.swindon.gov.uk/ep/ep-environmentalprotection/ep-environmentalprotection-nuisances/Documents/NOISE%20INFO%20PACK%20(NEIGHBOUR).pdf

Tachouali, D. & Taleb, H. (2015). Achieving energy reduction by applying passive cooling strategies in a hot arid region: a case study of the UAE. *WIT Transactions on Ecology and the Environment,* **193,** 1105-1115.

Taddyforde, K. K., Hobday, E., Rust, J., Cruden, W., Watney, H. & Mervyn (1877). *Gardeners' Chronicle A Weekly Illustrated Journal of Horticulture and Allied Subjects, Volume VII*. London: Haymarket Publishing.

Taiz, L. & Zeiger, E. (1998). *Plant physiology*. 2nd ed. Sutherland, MA: Sinauer Associates.

Takakura, T., Kitade, S. & Goto, E. (2000). Cooling effect of greenery cover over a building. *Energy and Buildings,* **31,** 1-6.

Tam, V. W., Zhang, X., Lee, W. & Shen, L. (2011). Applications of extensive green-roof systems in contributing to sustainable development in densely populated cities: A Hong Kong study. *Construction Economics and Building,* **11,** 15-25.

Taylor, J. E. (2012). *Green walls: The thermoregulatory role of plants adjacent to brick walls in a temperate climate.* PhD Thesis, University of Reading.

Taylor, M. (2017). *Revealed: Every Londoner breathing dangerous levels of toxic air particle*. The Guardian, (Last updated 16.31 BST on 4th Oct 2017). URL: https://www.theguardian.com/environment/2017/oct/04/revealed-every-londoner-breathing-dangerous-levels-of-toxic-air-particle: [12/07/2018].

Tedesco, S., Giordano, R. & Montacchini, E. (2016). How to measure the green façade sustainability? A proposal of a technical standard. *Energy Procedia,* **96,** 560-567.

The Council of the European Union (1999). Council Directive 1999/30/EC of 22 April 1999 relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air. *Official Journal of the European Communities,* **163,** 41-46.

The Ecology Consultancy & The Green Roof Consultancy (2012). *Better Bankside business improvement district green infrastructure audit and feasibility study.* London: The Ecology Consultancy & The Green Roof Consultancy.

The Engineering Tool Box. (2003). *Specific heat of common substances*. URL: https://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html: [07/07/2018].

The National Archives. (2018). *Localism Act 2011*. URL: http://www.legislation.gov.uk/ukpga/2011/20/contents/enacted: [31/07/2018].

The Stationery Office (1990). *Town and country planning act 1990.* London: TSO (The Stationery Office).

The Stationery Office (2010a). *Community infrastructure levy, England and Wales.* London: TSO.

The Stationery Office (2010b). *Fuel poverty: Fifth report of session 2009-10, Vol. 2: Oral and written evidence*. London: TSO.

The World Bank. (2017). *Population Growth (annual %)*. URL: https://data.worldbank.org/indicator/SP.POP.GROW?cid=GPD_2&locations=GB: [26/03/2018].

The World Bank & The International Monetary Fund (2013). *Rural-urban dynamics and the millennium development goals*. Washington: The World Bank URL: http://pubdocs.worldbank.org/en/961951442415876455/GMR-2013-Full-Report.pdf: [09/02/2019]

Time and Date AS. (2018). *June 2015 Weather in Reading — Graph.* URL: https://www.timeanddate.com/weather/uk/reading/historic?month=6&year=2015: [20/09/2018].

Thomas, M. (2015). *Case study - greening the BIDs: Private-public collaboration to deliver green infrastructure opportunities*. URL: http://www.c40.org/case_studies/greening-the-bids-private-public-collaboration-to-deliver-green-infrastructure-opportunities: [31/03/2018].

Thomsit-Ireland, F., Blanuša, T., Essah, E. & Hadley, P. (2016). Controlling ivy attachment to wall surfaces by applying paints, metal meshes and sheets. *Journal of Living Architure*, **3,** 1-14.

Thurston, M. (2014). *Key themes in public health*. Abingdon: Routledge.

Timonen, K. L., Vanninen, E., de Hartog, J., Ibald-Mulli, A., Brunekreef, B., Gold, D. R., Heinrich, J., Hoek, G., Lanki, T., Peters, A., Tarkiainen, T., Tiittanen, P., Kreyling, W. & Pekkanen, J. (2005). Effects of ultrafine and fine particulate and gaseous air pollution on cardiac autonomic control in subjects with coronary artery disease: The ULTRA study. *Journal of Exposure Science and Environmental Epidemiology,* **16,** 332-341.

Tong, Z., Baldauf, R. W., Isakov, V., Deshmukh, P. & Zhang, K. M. (2016). Roadside vegetation barrier designs to mitigate near-road air pollution impacts. *Science of The Total Environment,* **541,** 920-927.

Townshend, D. & Duggie, A. (2007). *Study on green roof application in Hong Kong.* Hong Kong: Urbis Ltd.

Treebox. (2014a). *Case Study: Commercial*. URL: http://www.treebox.co.uk/casestudy/commercial_0.html: [23/03/2018].

Treebox. (2014b). *Case Study: Residential*. URL: http://www.treebox.co.uk/casestudy/residential_0.html: [23/03/2018].

Tremper, A. H. & Green, D. C. (2018). *The impact of a green screen on concentrations of nitrogen dioxide at Bowes Primary School, Enfield.* London: King's College London. URL: https://www.londonair.org.uk/london/reports/Green_Screen_Enfield_Report_final.pdf: [28/02/2019]

Ulrich, R. S. (1984). View through a window may influence recovery from surgery. *Science,* **224,** 420-421.

United Nations Framework Convention on Climate Change (2019). *What is the Kyoto Protocol?* URL: https://unfccc.int/process-and-meetings/the-kyoto-protocol/what-is-the-kyoto-protocol/what-is-the-kyoto-protocol: [28/02/2019]

Urban Hygiene Ltd. (2014). *easy-on™ Protective coating technical data.* [Technical data sheet]. Doncaster: Urban Hygiene Ltd. URL: https://www.urbanhygiene.com/wp-content/uploads/2016/07/easy-on-Data.pdf: [20/01/2019]

Van Renterghem, T., Hornikx, M., Forssen, J. & Botteldooren, D. (2013). The potential of building envelope greening to achieve quietness. *Building and Environment,* **61,** 34-44.

Vardoulakis, S., Fisher, B. E. A., Pericleous, K. & Gonzalez-Flesca, N. (2003). Modelling air quality in street canyons: A review. *Atmospheric Environment,* **37,** 155-182.

Vaz Monteiro, M., Blanuša, T., Verhoef, A., Richardson, M., Hadley, P. & Cameron, R. W. F. (2017). Functional green roofs: Importance of plant choice in maximising summertime environmental cooling and substrate insulation potential. *Energy and Buildings,* **141,** 56-68.

Venkanna, B. K. (2010). *Fundamentals of heat and mass transfer*. New Dehli :Prentice-Hall of India (PHI) Private Limited.

Victoria BID (2014). *Victoria 2020 a vision for a vibrant Victoria: Victoria business improvement district (BID) BID renewal proposal 2015-2020.* London: Victoria BID.

Victoria BID (2013). Green infrastructure audit: Best practice guide. London: Victoria BID.

Viles, H., Sternberg, T. & Cathersides, A. (2011). Is ivy good or bad for historic walls? *Journal of Architectural Conservation,* **17,** 25-41.

Wagar, J. A. & Barker, P. A. (1993). Effectiveness of three barrier materials for stopping regenerating roots of established trees. *Journal of Arboriculture,* **19,** 332-332.

Wang, Y., Bakker, F., de Groot, R. & Wörtche, H. (2014). Effect of ecosystem services provided by urban green infrastructure on indoor environment: A literature review. *Building and Environment,* **77,** 88-100.

Watt, D. S. (2009). *Building Pathology: Principles and Practice*. 2^{nd} ed. Oxford: Blackwell Publishing.

Weber, F., Kowarik, I. & Säumel, I. (2014). Herbaceous plants as filters: Immobilization of particulates along urban street corridors. *Environmental Pollution,* **186,** 234-240.

Webster, A. D., Altkinson, C. J., Lucas, A. S., Vaughan, S. P. & Taylor, L. (2000). Interactions between root restriction, irrigation and rootstock treatments on the growth and cropping of 'Queen Cox' apple trees: Effects on orchard growth and cropping. *The Journal of Horticultural Science and Biotechnology,* **75,** 181-189.

Webster, A. D., Atkinson, C. J., Vaughan, S. J. & Lucas, A. S. (1997). Controlling the shoot growth and cropping of sweet cherry trees using root pruning or root restriction techniques. *ISHS Acta Horticulturae,* **451,** 643-652.

Weerakkody, U., Dover, J. W., Mitchell, P. & Reiling, K. (2017). Particulate matter pollution capture by leaves of seventeen living wall species with special reference to rail-traffic at a metropolitan station. *Urban Forestry & Urban Greening,* **27,** 173-186.

Weerakkody, U., Dover, J. W., Mitchell, P. & Reiling, K. (2018). Evaluating the impact of individual leaf traits on atmospheric particulate matter accumulation using natural and synthetic leaves. *Urban Forestry & Urban Greening,* **30,** 98-107.

Weißenbach, K. and Standke, B. (2001). Anti-graffiti and easy-to-clean properties on porous mineral surfaces are achieved by using waterborne fluoroalkylsilane systems. In: Littmann, K. & Charola, A. E. (eds.), *Third International Conference on Surface Technology with Water*

Repellent Agents. Hanover, Germany. September 2001. Unterengstringen: Aedificatio Publishers. pp 257-264.

Weißenbach, K., Standke, B. & Jenkner, P. (2008). Water-borne fluoroalkylsilanes: A new family of products for surface modification. In: Auner, N. & Weis, J. (eds.), *Organosilicon Chemistry V*. Weinheim: Wiley-VCH Verlag GmbH. Ch. 89

Westgate, M. E. & Boyer, J. S. (1985). Osmotic adjustment and the inhibition of leaf, root, stem and silk growth at low water potentials in maize. *Planta,* **164,** 540-549.

Westminster City Council (2016a). *Marylebone low emission neighbourhood: Westminster City council's bid to the Mayor's air quality fund*. London: Westminster City Council.

Westminster City Council (2016b). *Westminster City plan: Consolidated with all changes since November 2013*. London: Westminster City Council.

Wheeler, D. M., Power, I. L. & Edmeades, D. C. (1993). Effect of various metal ions on growth of two wheat lines known to differ in aluminium tolerance. *Plant and Soil,* **155,** 489-492.

White, E. V. & Gatersleben, B. (2011). Greenery on residential buildings: Does it affect preferences and perceptions of beauty? *Journal of Environmental Psychology,* **31,** 89-98.

Whitford, M. J. (1992). *Getting rid of graffiti: A practical guide to graffiti removal and anti-graffiti protection*. London: E & FN Spon-Chapman & Hall.

WHO (2006). *WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide. Global update 2005*. Geneva: World Health Organization.

WHO (2013). *Health effects of particulate matter. Policy implications for countries in eastern Europe, Caucasus and central Asia*. Copenhagen: World Health Organization.

WHO (2016). *Ambient air pollution: A global assessment of exposure and burden of disease.* Geneva: World Health Organization.

Wilcox, D. (1998). *The guide to development trusts and partnerships*.
URL: http://partnerships.org.uk/pguide/trusts.htm: [12/02/2018].

Williams, N. S. G., Rayner, J. P. & Raynor, K. J. (2010). Green roofs for a wide brown land: Opportunities and barriers for rooftop greening in Australia. *Urban Forestry & Urban Greening,* **9,** 245-251.

Willis, A. J. (1997). Forum - the ecosystem: An evolving concept viewed historically. *Functional Ecology,* **11,** 268-271.

Wilson, E. O. (1984). *Biophilia*. Cambirdge, MA: Harvard University Press.

Wong, N. H., Jusuf, S. K., Syafii, N. I., Chen, Y., Hajadi, N., Sathyanarayanan, H. & Manickavasagam, Y. V. (2011). Evaluation of the impact of the surrounding urban morphology on building energy consumption. *Solar Energy,* **85,** 57-71.

Wong, N. H., Kwang Tan, A. Y., Chen, Y., Sekar, K., Tan, P. Y., Chan, D., Chiang, K. & Wong, N. C. (2010a). Thermal evaluation of vertical greenery systems for building walls. *Building and Environment,* **45,** 663-672.

Wong, N. H., Kwang Tan, A. Y., Tan, P. Y., Chiang, K. & Wong, N. C. (2010b). Acoustics evaluation of vertical greenery systems for building walls. *Building and Environment,* **45,** 411-420.

Wong, N. H., Tan, A. Y. K., Tan, P. Y. & Wong, N. C. (2009). Energy simulation of vertical greenery systems. *Energy and Buildings,* **41,** 1401-1408.

Wood, A., Bahrami, P. & Safarik, D. (2014). *Green walls in high-rise buildings: An output of the CTBUH sustainability working group*. Victoria, Australia: Images Publishing.

Wu, Y., Zhao, X. & Zhang, M. (2010). Adhesion mechanics of ivy nanoparticles. *Journal of Colloid and Interface Science,* **344,** 533-40.

Wullschleger, S. D., Meinzer, F. C. & Vertessy, R. A. (1998). A review of whole-plant water use studies in tree. *Tree Physiology,* **18,** 499-512.

Xia, L., Lenaghan, S. C., Zhang, M., Wu, Y., Zhao, X., Burris, J. N. & Neal Stewart, C. (2010). Characterization of English ivy (*Hedera helix*) adhesion force and imaging using atomic force microscopy. *Journal of Nanoparticle Research,* **13,** 1029-1037.

Xiangjing, Z. (2011). *Test and validation of building energy simulation tools.* Master of Science Master Thesis, National University of Singapore.

Xuan, C. & Su-Jong, J. (2018). Shifting the urban heat island clock in a megacity: A case study of Hong Kong. *Environmental Research Letters,* **13,** 014014. URL: http://stacks.iop.org/1748-9326/13/i=1/a=014014. [06/03/2019]

Yang, D. S., Son, K.-c., Pennisi, S. V. & Kays, S. J. (2009). Screening indoor plants for volatile organic pollutant removal efficiency. *Horticultural Science,* **44,** 1377-1381.

Yang, L., Zheng, B., Mao, C., Qi, X., Liu, F. & Wu, P. (2004). Analysis of transcripts that are differentially expressed in three sectors of the rice root system under water deficit. *Molecular Genetics and Genomics,* **272,** 433-442.

YBS Insulation. (2017). *Airtec Technical*. URL: http://www.ybsinsulation.com/brands/airtec/airtec-technical/: [13/12/2017].

Yeager, T., Wright, R., Fare, D., Gilliam, C., Johnson, J., Bilderback, T. & Zondag, R. (1993). Six state survey of container nursery nitrate nitrogen runoff. *Journal of Environmental Horticulture,* **11,** 206-208.

Your local Guardian. (2011). Plants in controversial Sutton high street green wall die. *Your local Guardian*. URL: http://www.yourlocalguardian.co.uk/news/suttonnews/9339544.Plants_in_controversial_green_wall_die/: [06/03/2019]

Zhang, M., Liu, M., Prest, H. & Fischer, S. (2008). Nanoparticles secreted from ivy rootlets for surface climbing. *Nano Letters,* **8,** 1277-1280.

Zhang, W.-K., Wang, B. & Niu, X. (2015). Study on the adsorption capacities for airborne particulates of landscape plants in different polluted regions in Beijing (China). *International Journal of Environmental Research and Public Health,* **12,** 9623-9638.

Zhang, X. L., Li, K. L. & Skitmore, M. (2013). Creeping insulation - Hong Kong green wall. *International Journal of Environmental and Ecological Engineering,* **7,** 729-734. URL: https://waset.org/Publications/creeping-insulation-hong-kong-green-wall/17265: [06/03/2019]

Zonen, K. (2018). *Instruction Manual - CMP series • Pyranometer.* URL: http://www.kippzonen.com/Download/72/Manual-Pyranometers-CMP-series-English: [26/08/2018]

Appendices

Appendix A Drawing models in IES software

IES is a modelling package designed to perform complex calculations based on inputs and scenarios. As such there are several 'quirks' of the system which are neither visually pleasing nor intuitive. There are two methods of drawing buildings to be modelled within the software using the drawing module 'ModelIT'. The first way involves drawing the internal volumes of rooms (walls are visually a line's width); then the thickness of the construction materials are used to calculate the U-values for the heat transfer calculations. The heat transfer calculations are performed on each 'room' surface by comparing the temperature on either side of the surface at specified time periods (10 minute intervals were used with an hour reporting period (which provided a balance between speed of the simulation and storage size of the simulated data). While this method was intended for drawing over a CAD file to model a building designed by an architect (as described in the 'ModelIT' tutorial (IES, n.d.)); the method was used during the model validation in Chapter 4; as altering external wall construction thickness had no impact on the internal measurements of the modelled building.

An alternative method of drawing the modelled building involves marking the external walls, and the internal volume of the building is generated from the thickness of the construction materials. This method was employed for Chapter 4 sections 4.2 Figure 4.1a, and section 4.2.4 Figure 4.3a as the image is visually similar to the experimental buildings constructed in Chapter 3. If the thickness of the external wall construction materials is changed, however, the internal volume changes accordingly, and as several external wall materials of different thicknesses (with constant external dimensions) were modelled, this method was not used for simulation.

Appendix B Construction materials in IES

The construction materials used in the simulation were matched as closely as possible to building materials used for the 'brick cuboids' in Chapter 3, and where necessary values for the parameters were found on websites relating to the materials or derived. In IES software, the thermal resistance cannot be entered manually and is calculated from the thermal conductivity.

None of the insulation options in the IES construction materials database matched the 'silvered insulation' (see Chapter 2 section 2.6.1) used in the ceiling and floor of the brick cuboids, therefore the values for density and thermal conductivity for the insulation were derived numerically from values on the manufacturers website (equations [B.1] - [B.6]). A 25 m roll of 1.05 m wide single sided foil covered insulation weighed 5.1 kg, and would cover an area of 26.25 m^2. While the manufacturer (YBS Insulation, 2017) quoted the thickness as 0.004 m, the measured thickness was 0.0026 ± 0.0003 m, which was used in the calculations. The volume of a cuboid (equation [B.1]):

$$area * thickness\ (height) = volume \qquad \textbf{[B.1]}$$

Therefore the volume of the roll was (equation [B.2]):

$$26.25\ \mathrm{m}^2 * 0.0026\ \mathrm{m} = 0.0683\ \mathrm{m}^3 \qquad \textbf{[B.2]}$$

The density is calculated using the volume and the weight (equation [B.3]):

$$weight/volume = density \qquad \textbf{[B.3]}$$

Therefore the density was (equation [B.4]):

$$5.1\ \mathrm{kg}/0.0683\ \mathrm{m}^3 = 75\ \mathrm{kgm}^{-3} \qquad \textbf{[B.4]}$$

In the information on the manufacturing website (YBS Insulation, 2017) the thermal resistance of the foil covered insulation was specified as 0.125 m^{2}KW^{-1}, and from this value the thermal conductivity (Wm^{-1}K^{-1}) could be calculated (equations [B.5] and [B.6]).

$$1/thermal\ resistance * thickness = thermal\ conductivity \qquad \textbf{[B.5]}$$

$$1/(0.125\ \mathrm{m^2K}/\mathrm{W}) * 0.0026\ \mathrm{m} = 0.021\ \mathrm{W}/\mathrm{mK} \qquad \textbf{[B.6]}$$

The thickness of the bitumen felt used on the experimental brick cuboids was measured on three buildings in two places, with digital calipers and the mean thickness was 1.3 ± 0.1 mm. The vapour resistivity for the 'silvered insulation' was set to the same as the damp-proof membrane as the foil insulation can be used as a vapour barrier. All the thermal and physical properties of the construction materials, other than those specified above, were supplied by the closest description in the IES construction database. The roof, ceiling and floor remained constant throughout the model validation process; however different walls were tested (Table B.1).

Table B.1 Construction materials: construction layers listed externally to internally; specific heat capacity (SHC).

Zone	Material	Thickness (mm)	Conductivity (W/mK)	Density (kg/m^3)	SHC (J/kgK)	Resistance (m^{2}K/W)	Vapour resistivity (GNs/kgm)	Thermal mass (kJ/m^{2}K)
Roof/ Ceiling	Bitumen felt	1.3	0.5	1700	1000	0.0026	15000	0.20
	OSB	11	0.14	650	2000	0.0786	200	
	Cavity	18				0.18		
	Foil covered insulation	2.6	0.021	75	1030	0.125	1050	
Floor	Stabilising cement	10	0.16	500	840	0.0625	50	17.89
	PVC membrane	2	0.16	1379	1004	0.0125	1050	
	Aerated concrete slab	34	0.16	500	840	0.2125	50	
	PVC membrane	2	0.16	1379	1004	0.0125	1050	
	Cavity	18				0.18		
	Foil covered insulation	2.6	0.021	75	1030	0.125	1050	
	Cavity	18				0.18		
	Plywood	18	0.15	700	1420	0.12	1250	
Wall	Brickwork	103	0.84	1700	800	0.1226	0	70.04

The parameters defined within the IES construction materials database, provide information on one additional heat transfer parameter, and that is thermal diffusivity, or thermal inertia, which is the rate at which temperature changes are transferred through materials (Venkanna, 2010). The thermal diffusivity is calculated from the thermal conductivity, the specific heat capacity (SHC), and the density of a material, according to equation [B.7] (Venkanna, 2010).

$$thermal\ diffusivity = \frac{thermal\ conductivity}{SHC * density} \qquad [\ B.7\ ]$$

The thermal diffusivity of the construction elements indicates the rate at which changes in the local environment (for example, sunshine duration) will affect the internal environment of the cuboids. The higher the thermal diffusivity, the more rapidly changes in the external environment will transfer to changes in the internal environment (indicating less temporal lag).

Appendix C Estimating diffuse from global solar radiation

The diffuse component of the global solar radiation on the horizontal plane can be estimated using two parameters, the diffuse fraction k_d and the clearness index k_t (Lee et al., 2017). The clearness index and diffuse fraction are calculated from equations [C.1]and [C.2] where I_G, I_d, and I_O are the global, diffuse and extra-terrestrial solar radiation measured on the horizontal plane.

$$\frac{I_G}{I_O} = k_t \quad \text{[C.1]}$$

$$\frac{I_d}{I_G} = k_d \quad \text{[C.2]}$$

Erbs Model

The Erbs model (Erbs et al. cited by, Burgess, 2015) approximates k_d for different values of k_t using equations [C.3]-[C.5].

$$k_d = 1.0 - 0.249k_t \qquad k_t \leq 0.22 \quad \text{[C.3]}$$

$$k_d = 0.9511 - 0.1604k_t + 4.388{k_t}^2 - 16.638{k_t}^3 + 12.336{k_t}^4 \qquad 0.22 < k_t \leq 0.8 \quad \text{[C.4]}$$

$$k_d = 0.165 \qquad k_t > 0.8 \quad \text{[C.5]}$$

Once the appropriate value for k_d has been estimated, the diffuse component of the solar radiation can be calculated by rearranging equation [C.2] as per equation [C.6].

$$I_d = k_d * I_G \quad \text{[C.6]}$$

Estimating the direct normal from the diffuse and the global horizontal components

The direct (beam) solar radiation measured on the normal plane (perpendicular to the sun rays) G_n can be estimated from the diffuse and global solar radiation measured on the horizontal using equation [C.7] where θ_z is the zenith angle (Lee et al., 2017).

$$G_n = \frac{I_G - I_d}{\cos\theta_z} \quad \text{[C.7]}$$

The solar zenith angle is the angle of the sun in the sky, measured from the zenith (directly overhead), when the angle is 0^{o} and tends towards 90^{o} on the horizon when the sun is rising or setting (Figure C.1).

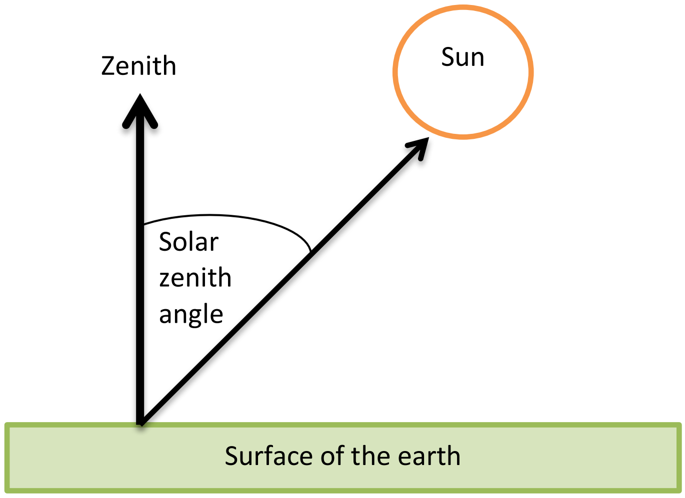

Figure C.1 Solar zenith angle

The cosine of the solar zenith angle can be calculated using equation [C.8] where δ is the solar declination, φ is the latitude, which for University of Reading is 51.44°N, and h is the local hour angle of the sun (Jacobson, 2005). As this equation was calculated in Microsoft Excel all the angles were converted to radians to function with the interface.

$$\cos\theta_z = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos h \qquad \textbf{[C.8]}$$

The solar declination represents the angle between the sun's rays and the equatorial plane (Figure C.2; Page (2003))

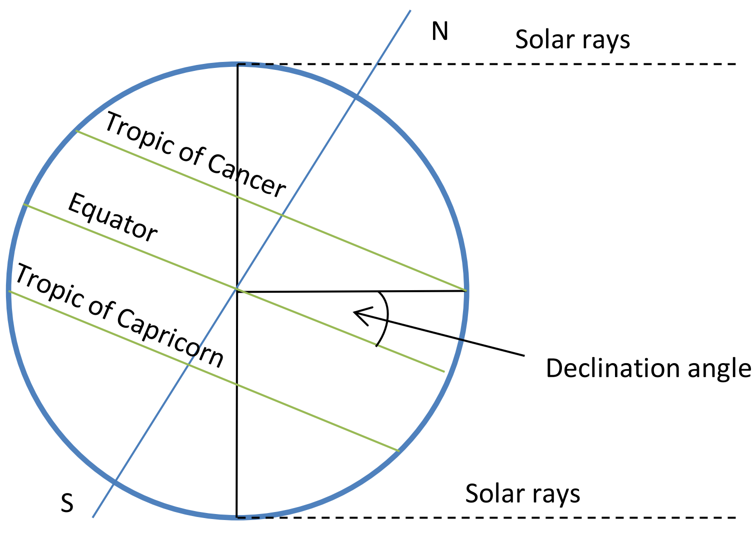

Figure C.2 Solar declination angle

A mean daily solar declination can be calculated using equation [C.9] where J_r is the day angle in radians (which is the Julian day number x 2π/365.25, and the Julian day number is the day of the year in numerical order from 1 - 365/6).

$$\delta = \sin^{-1} 0.3978 \sin[J_r - 1.400 + 0.0355 \sin(J_r - 0.0489)] \quad \textbf{[C.9]}$$

The local hour angle of the sun (h) is the angular form of solar time (see below) and is given by the equation [C.10] where LAT is local apparent time (Page, 2003).

$$h = 360 * (LAT - 12) \quad \textbf{[C.10]}$$

LAT is sometimes known as solar time and is referenced to solar noon where the sun is precisely due south (for the northern hemisphere), which is given by equation [C.11] where LMT is the local mean time, in Reading it was Greenwich mean time (GMT), however, as this data was to be used in the weather file where there is no daylight saving applied, GMT was used throughout the year. Additionally, λ is the longitude of the site in degrees which was -0.94 for UoR and λ_R is the longitude of the time zone the site lies within, which for Reading was Greenwich which is at longitude 0^o, c is the correction factor for daylight savings which was not used when calculating the LAT for this project as explained above. For Reading and the project, the formula could be simplified to equation [C.12]. The EOT is the equation of time which "is the difference in time between solar noon at longitude 0^o and 12:00 GMT on that day" (Page, 2003) and is calculated as equation [C.13] in hours and J_d is the day angle in degrees (the Julian day number (see above) x 360/365.25).

$$LAT = LMT + \frac{(\lambda - \lambda_R)}{15} + EOT(-c) \quad \textbf{[C.11]}$$

$$LAT = GMT + \frac{\lambda}{15} + EOT \quad \textbf{[C.12]}$$

$$EOT = -0.128 \sin(J_d - 2.80^o) - 0.165 \sin(2J_d + 19.7^o) \quad \textbf{[C.13]}$$

Appendix D Determining the ventilation of the brick cuboids

One unmortared and 14 mortared brick cuboids were selected to test the 'buildings' ventilation rates. The brick cuboids were bare or covered with *Hedera*, *Pileostegia* or *Parthenocissus*; cuboids 1, 3, 4, 6-8, 10, 11, 14-20 were measured, cuboid 17 was unmortared and bare (the planted *Parthenocissus* had died); the plants that covered the cuboids are identified in Chapter 2 section 2.7.

The experiment commenced on 27th July and concluded on 10th August 2016, the probe from a Testo 435-2 multifunction indoor air quality meter (Testo Ltd, Hampshire, UK) was placed inside each brick cuboid to measure the background concentration of CO_2 in the air (mean 395 ppm ± 43; 75 ppm ± 3% measured value, errors associated with the meter) and the meter was retained outside the cuboid. The Testo 435-2 multifunction indoor air quality meter also measured RH and temperature, however, in this case only CO_2 was required for this work. One gram of solid CO_2 (dry ice) was divided into several pieces, placed inside the building, and the CO_2 concentration was measured until the concentration reached at least 2500 ppm (or peaked for the unmortared cuboid), then the CO_2 source was removed. The logger recorded the concentration levels of carbon dioxide (ppm) every minute until the values decayed to the background concentration the then probe was removed; as the internal volume of the cuboids was small, the air and CO_2 were assumed to be well mixed. Once data was collected from brick cuboids, the time was converted into hours. The background CO_2 concentration measured for each cuboid was subtracted from the measured CO_2 concentrations, the decay curves were transformed with natural logarithms and linear trend lines plotted. The background CO_2 concentrations varied from 353-511 ppm (Table D.1).

Table D.1 Mean background concentration CO_2 (ppm; three measurements) inside the brick cuboids; 28th July 2016

Cuboid	Background CO_2 concentration (ppm) and standard deviation
Cuboid 1	361 ± 2
Cuboid 3	353 ± 5
Cuboid 4	428 ± 4
Cuboid 6	374 ± 1
Cuboid 7	371 ± 4
Cuboid 8	436 ± 10
Cuboid 10	388 ± 5
Cuboid 11	412 ± 9
Cuboid 14	361 ± 8
Cuboid 15	422 ± 9
Cuboid 16	373 ± 6
Cuboid 18	371 ± 1
Cuboid 19	368 ± 7
Cuboid 20	511 ± 17
Cuboid 17 (unmortared cuboid)	378 ± 8

The data was plotted as a scatterplot for each brick cuboid, then analysed and matched to the best-fit linear trend-line (occasionally a few points at the start just after the peak, and a few points towards the end as the CO_2 concentration reached atmospheric levels, were trimmed). Then a trend-line with equation was applied to each dataset, the datasets were grouped by similar rates of infiltration (Figure D.1-D.5 and Table D.2).

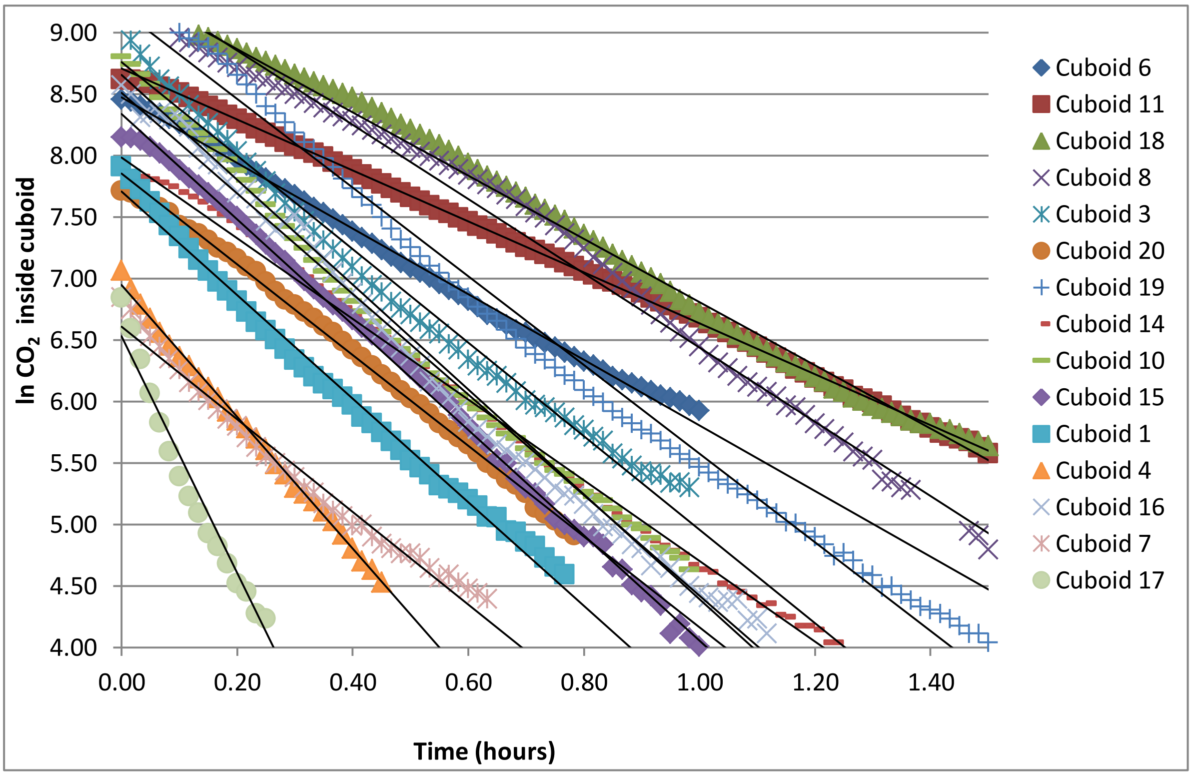

Figure D.1 Log. CO_2 concentration decay curves inside the brick cuboids versus time in hours with trend lines

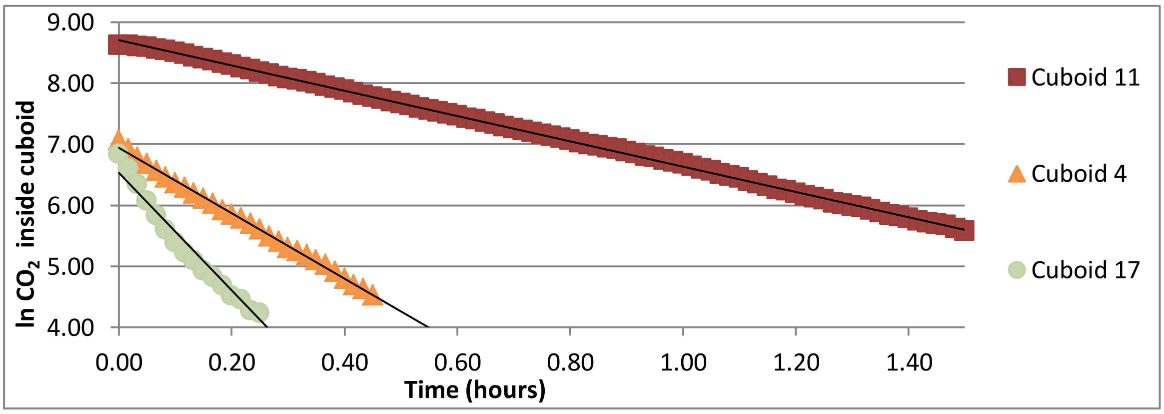

Figure D.2 Log. CO_2 concentration decay curves inside the brick cuboids versus time in hours with trend lines (extremes, i.e. most and least air tight and cuboid with no mortar)

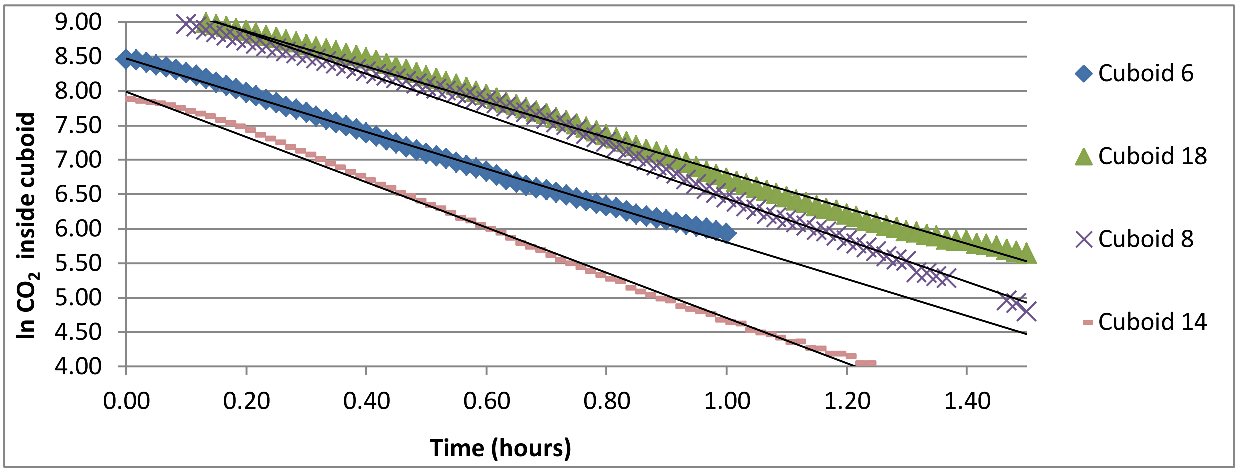

Figure D.3 Natural log. CO_2 concentration decay curves inside the brick cuboids versus time in hours with trend lines (grouped by similarity, excluding extremes, most air tight)

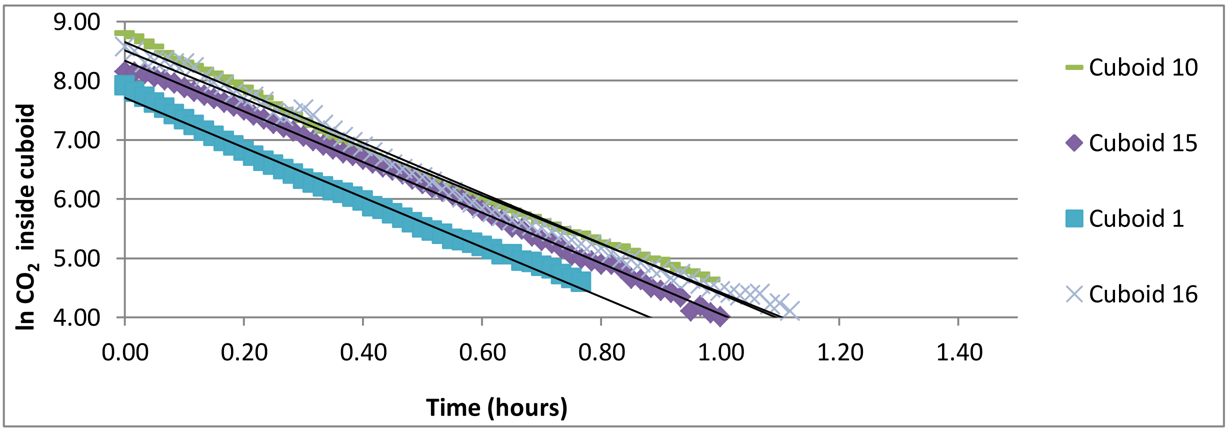

Figure D.4 Natural log. CO_2 concentration decay curves inside the brick cuboids versus time in hours with trend lines (grouped by similarity, excluding extremes, least air tight)

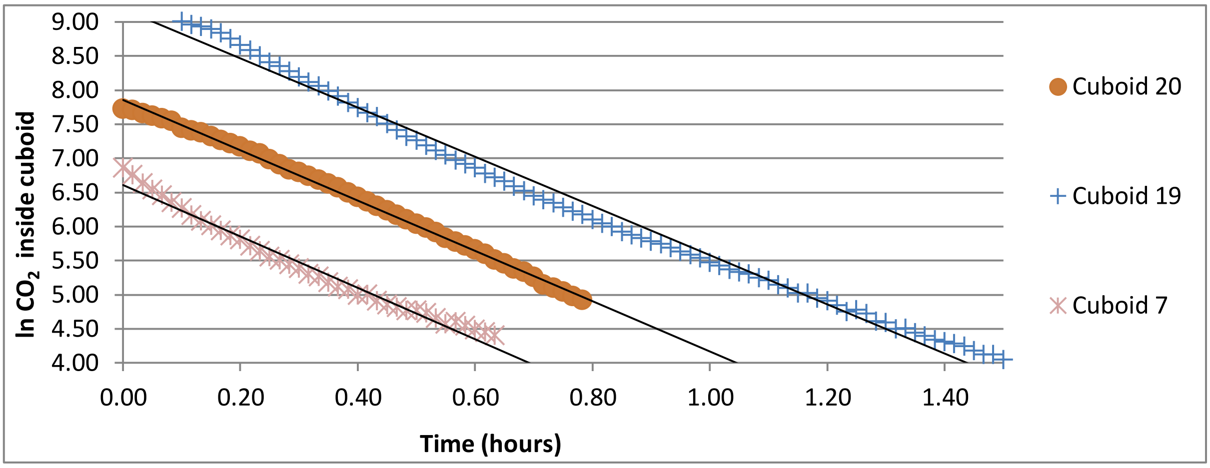

Figure D.5 Natural log. CO_2 concentration decay curves inside the brick cuboids versus time in hours with trend lines (grouped by similarity, excluding extremes, medium air tightness)

Table D.2 Linear equation for the trend-lines of the natural log. transformations of the CO_2 concentration decay curves for each brick cuboid and their associated coefficient of determination (in order of air tightness from least to most).

y = ax +b	a (slope)	B (intercept)	R^2 (coefficient of determination)
Cuboid 17 (unmortared bare)	9.62	6.53	0.98
Cuboid 4 (*Hedera*)	5.36	6.94	1.00
Cuboid 15 (*Hedera*)	4.28	8.34	1.00
Cuboid 10 (bare)	4.26	8.66	0.99
Cuboid 1 (bare)	4.21	7.71	0.99
Cuboid 16 (*Pileostegia*)	4.09	8.51	0.99
Cuboid 3 (bare)	3.80	8.76	0.99
Cuboid 7 (*Hedera*)	3.77	6.61	0.98
Cuboid 20 (bare)	3.69	7.85	1.00
Cuboid 19 (*Pileostegia*)	3.61	9.18	0.99
Cuboid 14 (*Parthenocissus*)	3.28	7.99	1.00
Cuboid 8 (*Parthenocissus*)	3.02	9.46	0.99
Cuboid 6 (*Pileostegia*)	2.67	8.48	1.00
Cuboid 18 (*Hedera*)	2.57	9.38	0.99
Cuboid 11 (*Parthenocissus*)	2.07	8.71	1.00

In a room, after a one-off release of a concentrated gas (not found in air), the concentration of that gas in the space follows an exponential decay over time, which can be expressed using the concentration decay function, equation [D.1](Laussmann and Helm, 2011):

$$C(t) = C_0 e^{-\Lambda t} \qquad \text{[D.1]}$$

C(t) is the concentration at time t.

C_0 is the concentration at time 0

Λ is the air changes per hour

t is time (in hours)

If, however, a gas which is found in the air is used (for example, CO_2), the exponential decay will not tend towards zero, but to the background concentration, as shown by the equation [D.2] where C_b is the background concentration of the gas

$$C(t) = (C_o - C_b) * e^{-(\Lambda t)} + C_b \qquad \text{[D.2]}$$

To represent this linearly and graphically, the concentration of the gas is presented in a natural logarithmic scale, versus the time which is presented as hours. For the trend-line of the logarithmic transformed decay curve y = ax + b, where the x axis is represented by time, ax is $-\Lambda t$, hence a = Λ or the air changes per hour, equation [D.3].

$$ln(C(t) - C_b) = -(\Lambda t) + ln(C_0 - C_b) \quad \textbf{[D.3]}$$

There have been concerns over using carbon dioxide as a tracer gas, mainly relating to the variation of CO_2 day to day, season to season, and potential difficulty with monitoring the external background concentration. For this reason it has been suggested that it may be more accurate to fit exponential trend curves to untransformed data and calculate the air changes from the exponential function and apply confidence intervals to this. As an approximate value for the air leakiness was appropriate for modelling different conditions in the building analysis software IES, the linear equation with the natural logarithmic transformation was used.

The results for the number of air changes per hour (as defined by the slope of the plots in Figure D.1-D.5 and Table D.2) shows that there were a wide range of building ventilations rates from 2.1 ACH to 5.4 ACH, with a mean for all the cuboids of 3.62 ± 0.85 ACH.

The building attributes and their varying ventilation rates were analysed, but there were no correlations with building position, mean foliage depth, or whether the building was mortared in the winter or spring (data not shown). This is also noticeable as there are mixtures of treatments (namely bare and plant-covered) in each of the groupings by similarity of air tightness (Figure D.1 - Figure D.5). Therefore, a factor of the constructions' air tightness may have been practise in mortaring the structures. The least air tight structures were cuboid numbers 4, 15, 10 (Table D.2) all of which were mortared in winter for the early spring experiment in March 2015. Although plant-covering may be an additional factor, as the six most air tight cuboids were all plant covered (Table D.2), the greater impact (as indicated by the fact that some of the *Hedera* covered buildings mortared in the 'first batch' were not as air tight as cuboids mortared later) was probably the quality of mortaring. As there was no significant difference between the vegetated buildings' and bare buildings' ventilation (data not shown) the mean air changes per hour of 3.6 ACH was used for all the buildings in the simulation.

Appendix E Causes of the phase shift in modelled cuboid validation

Phase Shift

When the data which was averaged for the experimental cuboids was analysed, there were times when the different sensors measuring temperature throughout the various brick cuboids could record peak temperatures up to two hours apart (this occurred both between buildings and between sensors along the south wall; during summer for the bare cuboids and March 2015 for both the bare and the *Hedera* covered cuboids). As the split timings for the measured peak temperatures did not occur every day, this could explain the lack of consistency in the one hour shift, hence, the phase shift was not applied in winter or for the *Hedera*-covered buildings (as there was not necessarily a benefit to applying it and its application in summer for the bare cuboids may explain the observed slight increase in absolute percentage difference).