THE ANIMAL BIODIVERSITY OF GREEN WALLS IN THE URBAN ENVIRONMENT

Caroline Chiquet

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“If you are not a little bit afraid every day, you are not trying hard enough.”
(Anonymous)

“Follow passion first and foremost.
Do valuable things that have little or nothing to do with your PhD. Be utterly busy with everything awesome and worthwhile.”
(Bradley L. Garrett)

ABSTRACT

Over the last few decades, a substantial body of literature has highlighted the importance of the natural environment for human well-being and health. In the urban environment where, space is particularly costly, the abundance of plants can be increased by growing them vertically as 'green walls', rather than horizontally. Although green walls ecology is a rapidly growing science, large gaps remain in our knowledge as only few studies have investigated their ecosystem services, focusing mainly on their thermal values. This doctoral research is one of the first attempts to establish the value of varying vertical greening systems for animal biodiversity. To identify the animal populations of green walls, surveys were carried out on bird, snail, spider and insect communities in green façades and living walls of Stoke-on-Trent, Birmingham and London, UK. The study then focused on the effects of varying characteristics of green walls (e.g. vegetation surface area, plant density and richness, botanical composition, type of foliage) on these communities and also investigated if the local environment (e.g. pedestrian and vehicle traffic volumes, abundance of nearby vegetation) influenced the use of green walls by animals. The results showed that animal groups respond differently to the characteristics of green walls and the surrounding features. Importantly, the design and the maintenance interventions of green walls influence their use by animals and, as such, it is possible to modify these environments to make them more attractive to certain animal communities. Whether growing on independent self-supporting structures, or directly on or in buildings, plants can use largely underexploited vertical space allowing an additional type of ecosystem to be incorporated into the urban environment.

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.

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LIST OF ABBREVIATIONS

CBD	Convention of Biological Diversity
GI	Green Infrastructure
GF	Green Façade(s)
GDP	Gross Domestic Product
GS	Green screen(s)
GW	Green Wall(s)
KW	Kruskall-Wallis test(s)
LAI	Leaf Area Index
LEED	Leadership in Energy & Environmental Design
LW	Living Wall(s)
LWS	Living Wall System(s)
MW	Mann-Whitney U test(s)
OCs	Organic Compounds
PAC	Particulate Abatement Capacity
PAHs	Polycyclic Aromatic Hydrocarbons
WT	Wilcoxon signed-rank test(s)
PM	Particulate Matter
PM_{10}	Particles less than 10 µm in aerodynamic diameter
$PM_{2.5}$	Particles less than 2.5 µm in aerodynamic diameter
PP	Polypropylene
SPM	Suspended Particulate Matter
SUDs	Sustainable Urban Drainage systems
TSP	Total Suspended Particulate
UH	Urban Hedge(s)
UHI	Urban Heat Island
US EPA	United State Environmental Protection Agency
VOCs	Volatile Organic Compounds
VU	Vulnerable status of species

LIST OF SYMBOLS

Al	Aluminium
C	Carbon
Ca	Calcium
Cd	Cadmium
Co	Cobalt
Cu	Copper
Fe	Iron
K	Potassium
Mg	Magnesium
Na	Sodium
NOx	Oxides of Nitrogen
O	Oxygen
P	Phosphorous
Pb	Lead
Pd	Palladium
Pt	Platinium
Si	Silicon
SOx	Sulphate
SO_2	Sulphur Dioxide
Ti	Titanium
Zn	Zinc

THESIS METHODOLOGY AND CHAPTER ORGANISATION

This thesis comprises eight chapters in four main sections: (i) the outline of the thesis, (ii) a literature review, (iii) the experimental research and discussion of the results, and (iv) a synthesis, the implications and the conclusions. The research methodology is given in diagrammatic form in Figure 1.

The first chapter gives a brief overview of the research area, the aims and objectives of the research and of the approach taken to answer the different research questions.

The second chapter contains the background to the work. It defines green walls within the wider concept of green infrastructure and includes a literature review focussed on their attributes and environmental values. It also briefly covers the importance of enhancing urban wildlife and the role green walls may play.

Chapter three describes the different study sites and gives the general methodology and statistical approaches used to analyse the data. Procedures specific to each taxon are detailed in the following chapters.

Chapters four to seven report the experimental work on the value of green façades and living walls for animal biodiversity, focusing in turn, on birds, snails, spiders and insects. Partly based on published or submitted work, these chapters are written as scientific articles and the results are individually discussed in each of them.

Chapter eight synthetises the findings and achievements of the project, and looks at their implications for design and utilisation of urban green walls. The thesis ends with recommendations for further work and the major conclusions that can be drawn.

CHAPTER I

THESIS OUTLINE

1. THESIS OUTLINE

Green walls (GW) refer to vertical greening systems, i.e. to vegetation growing on or against vertical surfaces. Whether growing naturally or as artificial man-made structures, they can be considered to be elements of green infrastructure. The ecology of green walls is an emerging discipline and the recent focus has been essentially on their potential ecosystem services. The latter has been the angle taken for this PhD project (see literature review in chapter 2).

1.1 AIMS AND OBJECTIVES OF THE DOCTORAL RESEARCH

When the present project started, no information could be found on the animal biodiversity of green walls in international peer-reviewed journals (although some information was later found in a book by Köhler (1993) in German). With the emergence of the use of green walls as part of the new science of ecological engineering applied to architecture (Haggag 2010; Sheweka & Magdy 2011), there was an urgent need to understand and get more information on the animal populations that could use urban green walls. The present project aimed to fill this gap. The focus was set on green façades and living walls, as the two main green wall types (see section 2.2.1 for definitions); and on the study of birds, shelled molluscs, spiders and insects for a diverse range of animal taxa. The primary objective was to answer the questions:

- Are green walls be more attractive to animals than bare walls?
- What animal populations are using green walls?

Once this first step was established, it was possible to address the following objectives:

- Establish which of, and how, the green wall's characteristics are influencing the animal populations.
- Examine if, and how, the surrounding features influence the use of GW by animal taxa.

Several research questions were raised; they were answered either by a literature review or by experimental studies (see Fig. 1).

1.2 PLANNING

The project started in April 2010. The first year's fieldwork was dedicated to (i) the finding of suitable green façades as sites of study, (ii) the development of surveys methods for mollusc, spider and insect populations, and (iii) the bird surveys. The second year was dedicated to (i) the invertebrate data collection on green façades and (ii) the design and installation of the new living wall system. During the third fieldwork season, living walls systems and green screens were surveyed.

It was initially planned to survey invertebrates in the spring, the summer and the autumn. Unfortunately, due to technical problems affecting the equipment, the suction sampling could not be used in the spring, so data are available only for the summer and the autumn.

1.3 JUSTIFICATION OF METHODS AND PILOT STUDY

Because no previous studies were found on animal surveys on vertical surfaces and due to the structural nature of green walls, particular attention was given to the methodology for invertebrate surveys. Several methods were tested during the first fieldwork season (in 2010) on green façades. For example, active sampling such as the use of a sweep-net on the outer leaves of the vegetation, and passive traps like sticky, coloured, and cross-vane window flight traps (equivalent to the multidirectional Polytrap™ (Brustel 2004)) were tested for insect sampling. Finally, only active traps were chosen to avoid random removal of passive trap by people. Due to the different vegetation composition of different green wall types and installations, the use of sweep-net was not found to give consistent results on each site. Therefore, a visual count method was chosen for birds, shelled molluscs, spider webs and spiders, plus the use of a vortis suction sampler for invertebrates.

During the same fieldwork season, a pilot study investigated the ideal amount of sampling per wall to achieve a good estimate of the invertebrate biodiversity. Carried out on ten green façades and ten bare walls, it showed that three samples per wall and season achieved the same estimate of animal populations (in terms of abundance and species richness of snails, spiders and insects) as four, five and six samples (see Appendix 1 for further details). Following this finding, three samples were taken per wall and per season in the subsequent fieldwork season on green façades.

1.4 CREATION OF A LIVING WALL ON THE UNIVERSITY CAMPUS

While launching the Master Plan for the improvement of the University Campus, the Executive team showed interest for the installation of a living wall (presented during a call for projects). The living wall, installed in spring 2011 on the side of the Henrion Building, was intended as an experimental project and was designed closely with the manufacturer (see section 3.1.3). The study of this living wall allowed investigation of the colonisation rate of animal species and their species ecological succession; whereas the study of the established green façades and living walls showed the animal biodiversity present after several year's growth.

CHAPTER II

LITERATURE REVIEW

2. LITERATURE REVIEW

This chapter will explore the definition of green infrastructure and the amenities its components provide. It will also examine how green walls were used in the past, describe the different types of green walls, and give specific examples of some current commercial systems. The extensive findings on the environmental values of green walls will be reported, together with a short review centred on animal biodiversity in urban areas.

2.1 GREEN WALLS: A GREEN INFRASTRUCTURE COMPONENT

2.1.1 Green infrastructure definition and services

Green infrastructure (GI) is an umbrella concept which brings together different vegetation-based components (Dover 2006), intended to solve urban and climatic challenges. A useful definition of green infrastructure was given by '*Biodiversity by Design: a guide for sustainable communities'* (in Dover 2006) which has been adopted here:

> "Green infrastructure is the sub-regional network of protected sites, nature reserves, greenspaces, and greenway linkages. […] Green Infrastructure should provide for multifunctional uses, i.e. wildlife, recreational and cultural experience, as well as delivering ecological services, such as flood protection and microclimate control. It should also operate at all spatial scales from urban centres through to open countryside."

Thus, GI components include green spaces such as parks and recreation grounds, urban forestry, rivers, streams, ponds, flood plains, street trees, Sustainable Urban Drainage systems (SUDs), green roofs, and green walls. They can be specific sites at the local level or broader environmental features at the landscape scale. Altogether, they define a network of natural and semi-natural features that intersperse and connect human settlements, and which have the potential to tackle several issues raised by the urban environment (Anonymous 2010a; Grant 2010).

Underpinning the multiple functions that GI perform is the concept of ecosystem services. At all scales, GI assets have the potential to deliver cost-effective solutions to many urban environmental problems and provide real economic, social and ecological benefits:

1. A green infrastructure approach can **promote business and investment**. For an enterprise, it sends a message of sustainability and a 'green image', highly valued by its clients and the public, and giving potential to fulfil the objectives of Corporate Social Responsibility (Makower 2012). The presence of quality green spaces in an area increases the local land and property values, attracts workers and tourism, and acts as a catalyst for regeneration (Jim & Chen 2010a).

2. In a hardscape environment, GI components can provide essential services in terms of **water and waste management**. Costs of stormwater management can be reduced with natural water storage (e.g. woodlands and wetlands), through natural percolation into the soil (infiltration) and groundwater, slowing the passage of water to streams and rivers. SUDs can also be used to attenuate surface-water run-off by absorbing excess rainfall, providing an effective and efficient soak-away, and thus reducing the risk of flooding (Ellis 2013). The need for waste management infrastructure can be reduced through, for example, the use of reed beds or other drainage systems that remove pollutants from water (Sansalone *et al.* 2013).

3. GI improves the **resilience of buildings and man-made features to climate changes**. This resilience includes both mitigation of, and adaptation to, climate change. Plants can reduce the urban heat-island effect through evapotranspiration, shading and decrease in solar heat gain (see Lundholm *et al.* 2010). GI assets, through passive heating and cooling, can reduce energy usage in buildings (McPherson *et al.* 1988 and references therein; Ferrante & Mihalakakou 2001), and through insulation improvement, can reduce CO_2 emissions (Wang *et al.* 2006). Climate change mitigation includes the creation of sustainable ways of energy and heat production, such as the reallocation of space for wind power, ground-source heating or biomass production, and the planting of trees to fix carbon in timber (Metz *et al.* 2007).

4. GI helps to improve the **air quality** in busy cities and to create healthy built environments. Vegetation traps atmospheric carbon dioxide (CO_2), gives off oxygen (O_2) but also acts as a filter for air and water pollutants, removing dust and particulates (Pugh *et al.* 2012).

5. Green infrastructure has a substantial role to play in the improvement of **quality of life** in urban areas (see Wells & Evans 2003 and references therein). For example, they can reduce the acoustic and light pollution of an area (Goode 2006; Tzoulas *et al.* 2007), soften the urban landscape (Grant 2010), provide shading (Dimoudi & Nikolopoulou 2003) and serve as windbreak (Ottelé 2011), while providing visual amenity (Bolund & Hunhammar 1999; Perini *et al.* 2011). They have been shown to have major positive impacts on **human health** (Tzoulas *et al.* 2007) and display many social benefits to individuals, organizations and the entire community (Westphal 2003). As such, the presence of vegetation and green spaces have been proven to help lower stress levels, increase longevity, improve recovery from illness and encourage exercise by providing local places for recreation (Kaplan & Kaplan 1989; Taylor *et al.* 2001; Frumkin 2003; Johnston & Newton 2004; Tzoulas *et al.* 2007; Jim & Chen 2010a). It can also enhance work performance in the office and increase job satisfaction (Kaplan & Kaplan 1989; Dravigne *et al.* 2008). Greening vacant lots has a positive influence on **anti-social behaviour** as it is correlated with a reduction of gun assaults and vandalism according to Branas *et al.* (2011). GI components can also be designed as a link between

different areas with the city and provide zero-carbon transport corridors through cycling or walking (Dover 2006).

6. GI components have been shown to enhance a **local sense of ownership and community** (Ellis 2013). The design and management of the assets can involve local residents and provide many volunteering and training opportunities. A green infrastructure approach is a way to reconnect city-dwellers with nature and provide many **educational opportunities** for children (Laaksoharju & Rappe 2010).

7. **Food production** can be enhanced through green infrastructure (e.g. allotments, community gardens, urban orchards). Through access to healthy food, the asset provides educational and business opportunities and reconnects communities with the local environment (van den Berg *et al.* 2010).

8. The value of green infrastructure for wildlife and enhancing **animal biodiversity** is well established. It provides habitats, food sources, protection and corridors for many species and allows additional species to dwell in the urban area (see section 2.4).

Our societal timescale - demographic, behavioural, socio-political, technological and economic - influences demand for goods and services. This alters the way humanity is managing ecosystems and natural resources, and the way it is using and responding to ecosystem services (Bolund & Hunhammar 1999; Pauleit & Duhme 2000).

2.1.2 The importance of green infrastructure

According to the United Nations, more than half of the world's population is currently living in urban areas and nearly 5 billion people, or 60% of the world population, are expected to be living in cities by 2030 (Heiling 2012). Despite the new inhabitants added each year to our cities (approximately 2% of annual growth rate according to Heiling (2012)), the total urban areas actually only cover less than 3% of the habitable surface of our planet (Potere & Schneider 2007). Due to global urbanisation and its biotic homogenisation, humanity is becoming increasingly disconnected from nature (Miller 2005; McKinney 2006), such that many urban-dwellers have little experience of the diversity of natural environments and do not comprehend the impact of weather, the seasonal rhythms and the constraints of time on nature (e.g. growth period, dormancy, flowering season - Hough 2002). Although throughout recorded history, people have always tried to incorporate nature in urban environments (Dunnett & Kingsbury 2008), it is only recently that the importance of the presence of nature for human well-being and health has been recognised (Tzoulas *et al.* 2007; Beatley & Newman 2013). As such, it is since the increased urbanisation of the nineteenth century (following the Industrial Revolution) that nature has been encouraged within cities to varying degrees, although it is almost always an 'altered' form of nature (Swanwick *et al.* 2003; Francis & Lorimer 2011; Jim

2012). Between 2009 and 2011, the UK National Ecosystem Assessment (Anonymous 2011) analysed the natural environment in terms of the benefits it provides to society and economic prosperity. The report stressed that human health and wellbeing, along with economic productivity, depend on the range of services provided by ecosystems (Watson & Albon 2011). However, translating the ecosystem services delivered by green infrastructure components into numbers is a complex task. Hence, it is difficult to attach a comprehensive economic value to the benefits or to the entire ecosystem (Anonymous 2008). This is why these services are often undervalued in conventional economic analyses and decision making (Watson & Albon 2011) although attempts to integrate them is growing (Lovell & Taylor 2013). Introducing nature into cities follows the ‘strand’ of conservation (alongside reserves and restoration) termed by Rosenzweig (2003a,b; 2004) as ‘reconciliation ecology’ (see also section 2.4). Studies have been carried out that have developed our understanding of children’s interaction with nature so that their environmental awareness can be educated (Hampel & Holdsworth 1996; Chapman & Sharma 2001; Meinhold 2005). The studies mainly showed that ideas about and interactions with nature may differ depending on the gender, and on the physical and socio-economic environment (Worsley & Skrzypiec 1998; Korhonen & Lappalainen 2004; Tuncer *et al.* 2005; Laaksoharju & Rappe 2010; Boeve-de Pauw & Petegem 2010; Aslan 2013). Nevertheless, and as for adults, the presence of nearby nature has been shown to moderate the impact of stressful life events on the psychological well-being of children (Wells & Evans 2003; Tzoulas *et al.* 2007).

The different challenges due to rising levels of urbanisation are often approached as separate issues for the purpose of communicating them clearly, despite the complex interactions between them (Anonymous 2009a; Grant 2010). Thus solutions for housing, nature preservation, stormwater management, and acoustic insulation, to mention only a few, are often considered individually. Consequently, each green infrastructure component is often installed for a single primary function (e.g. SUDs as storm-water management, street trees for softening the landscape - Davies *et al.* 2006). An integrated green infrastructure approach when planning for new - or improvement of existing - settlements can offer an alternative to this way of thinking, as in reality the performance of GI components are not easily separated. Instead of tackling challenges individually, GI assets can be seen to contribute to multiple benefits simultaneously. For example, street trees add aesthetic quality to an urban area, but will also reduce airborne pollution, provide shade, reduce urban heat island (UHI) effects, mitigate wind chill and turbulence, and increase biodiversity (Heisler 1986; Nowak 2000; Gratani *et al.* 2008; Helden *et al.* 2012). In addition, when GI components are connected, the benefits they generate can be maximised (Anonymous 2012a). Thus, connectivity creates an environment more adaptive and resilient to changes in climate such as increase in rainfall or heat waves (Anonymous 2012a). Physical connections of GI components also create corridors encouraging species migration and colonization (Dover 2006).

Green Infrastructure has a role in the main challenges urban areas face in the 21st century, which are how to provide healthy built environments, reconnect city-dwellers with nature and manage the different conflicting pressures for housing, industry, transport, energy, climate change, agriculture, nature conservation, recreation and aesthetics. As components of GI, green walls have the potential to deliver many of these benefits.

2.2 THE UMBRELLA CONCEPT OF GREEN WALLS

2.2.1 Green walls, definitions and characteristics. Proposal for classification

Green walls (GW) refer to vertical greening systems (Fig. 2.1), i.e. to vegetation growing on or against vertical surfaces. They can be found outdoors or indoors, in urban or rural areas. It can be any type of vertical surface, from building façades to freestanding structure (Ottelé 2011), either incorporated into new builds or easily retrofitted to existing building surfaces. By taking advantage of the vertical dimension, they are unique ecosystems that are not easily compared to those in the horizontal realm. They can vary considerably in construction (Dunnett & Kingsbury 2008), plants can be rooted into the ground, in the wall itself, off the ground in several types of growing media (mineral or organic), or in an inert medium acting only as a rooting element (i.e. soilless). According to the type of structure, the system can be either 'completely natural' or hydroponic. When required, irrigation can be manual or automatic. Green walls have been mainly divided into two main categories: green façades (GF) and living walls (LW) (Köhler 2008; Francis & Lorimer 2011). However, as the field is relatively new, the definition of what is, or is not, a green wall has not been completely resolved and terminology varies across papers (e.g. Köhler 2008; Ottelé 2011; Perini *et al.* 2011, 2013). Here, the concept of green wall is extended to a wider range of systems than indicated by most authors: urban hedges, masonry walls, green façades (including green screens), living curtains and living walls (Fig. 2.1 and 2.2). That is to say, any shrubby or herbaceous vegetation with a vertical dimension and creating a partition, with or without added support.

2.2.1.1 Living walls

Living walls (Fig. 2.2.a,b,c,d,l,m) are recently developed, completely artificial planted-up systems, using continuous or modular units (Weinmaster 2009). Continuous living wall systems (LWS) can be made of felt-layers of horticultural geotextile, foam, or of concrete panels sometimes called ‘green concrete’, either with large pores between the granular material used as the outer surface, or with a bio-foam/cement layer, for plants to root into (Ottelé 2011). Modular panels use modules of *Sphagnum spp*., substrate-filled metallic cages (also called gabions), preformed plastic modules, rockwool units, or moss mats (Köhler 2008; Ottelé 2011; Perini *et al.* 2013). Plants are rooted directly in the structure (in the case of felt layers, sphagnum units or foam boards) or in a growing medium, added to the structure beforehand (for concrete blocks, rockwool units, plastic preformed modules or gabions). The growing media can be organic such as coconut coir (*Cocos nucifera* L.), peat, tree bark, or inorganic materials such as expanded clay pebbles, gravel, perlite, mineral soil, mineral wool, sand, or vermiculite; it is common for different components to be used in mixes (see Dunnett & Kingsbury 2008; Carpenter 2014; Kevin 2012). Such systems are usually hydroponic (i.e. the mineral nutrients are brought to the plants as inorganic ions in irrigation water). However, some commercial organic substrates (e.g. gabions with organic media) are said to be self-sufficient in nutrients for at least 5-10 years (Schuurbiers pers. comm.).

Almost any plant species can be grown on a LWS; it supports any ground cover plants, ferns, low shrubs, perennial flowers, vegetable, herbs, etc. that do not naturally grow vertically. Typically, the only constraint is the weight of the mature plant; although some felt layer systems have been shown to support tree species (Blanc pers. comm.). Indoor walls are usually planted with tropical species due to the constant mild temperature and the low levels of light; while outdoor walls are more restricted to weather-resistant plants. Some plant species are now known to develop well on LW (see Appendix 2). LWS are sometimes referred to as “vertical gardens” either as an alternative name (Blanc 2008; Köhler 2008) or as when they are specifically used to grow herbs and/or plants producing vegetable or fruit. When growing herbs, the GW is usually informally called an “herb wall” (see e.g. Anonymous 2012b, 2013a). Depending on the system and the manufacturer, units are either pre-grown prior to installation in a greenhouse (vertically or not), or planted on site once installed (see also section 2.2.3).

2.2.1.2 Green façades

Green façades (Fig. 2.2.e, f, g, h) are made of climbing plants growing on a wall, either with no additional infrastructure or with the use of support. In the latter case, many materials can be used, such as coated, stainless or galvanized steel, wood, aluminium, and plastic to create a meshwork or cabling support (Perini *et al.* 2013). Cables are usually designed to support fast-growing climbers with dense foliage; wire-nets are more used for slow growing plants needing support at small intervals (Jakob® 2003). The support can keep the plant away from the wall (see section 2.3.3) and ease maintenance or removal. Traditionally, GF are set outdoors, rooted in the ground and do not require additional irrigation (Anonymous 2010b). Their simplest form, rooted in the ground and attached directly to the building, make them a relatively inexpensive, easy way of façade greening and in the form of a natural process without human interventions. Some authors make a distinction between green façades using support or not (respectively called indirect or direct greening systems, see Perini *et al.* 2013).

The great diversity of climbing plants, in terms of flower and foliage colours, flowering season, profile, etc. (see Appendix 3) makes them attractive for human-use (Dunnett & Kingsbury 2008). They can be evergreen or deciduous, are usually woody and perennial although some can be herbaceous and/or annual (Fitzgerald 1906; Squire 2005). They show many ways of adhering to a surface (see Appendix 4) and need different kinds of support, either vertical and/or horizontal, or even none at all (see Appendix 4 and section 2.3.2). Plants that can be trained against the wall or in espalier (e.g. *Camellia spp.*, *Ceanothus spp.*, *Chaenomeles spp.* flowering quince, *Coronilla valentine* scorpion vetch, *Fuchsia spp.*, *Garrya spp.*, *Magnolia grandiflora*, *Pyracantha spp.*), referred to as 'wall shrubs' (Fitzgerald 1906; Squire 2005), can be included in the term 'green façade'. The plant choice, typically taking three to five years before achieving full coverage, and the material choice of support, will affect the aesthetic and functional characteristics of the greened façades due to the different weights and final heights, the profile thickness and life span (Dunnett & Kingsbury 2008; Ottelé 2011).

Recently, a new type of green façade has been developed: called green screens (Gs - Fig. 2.2.h), they are made of climbing plant(s) (typically *Hedera sp.* outdoor and *Philodendron sp.* indoor), pre-grown on a freestanding, galvanized steel framework. They are established as an instant hedge or as a portable, reusable living hoarding (e.g. 'reusable living hoarding' from Treebox Ltd.), that can be set outdoor and/or indoor (e.g. 'WallPlanter' or 'Green Screens' from Mobilane®), with or without an irrigation system. The facts that (i) they are commercially pre-grown in a nursery, (ii) they can be completely free-standing when historically GF are against walls, and (iii) they are usually installed with automatic irrigation, set them apart as a sub-category of green façades.

2.2.1.3 Living curtains

Living or green curtains (Coyne & Knutzen 2010; Pérez *et al.* 2011a,b,c - Fig. 2.2.i,j,k) combine the features of both green façades and living walls; depending on author they are considered as belonging to either the GF or LW categories (Dunnett & Kingsbury 2008; Köhler 2008; Perini *et al.* 2011, 2013; Rutgers 2012). Like GF, this system is made of climbers growing up a structure; however, plants are rooted off the ground, in small planter boxes, as hydroponic systems like LWS (Köhler 2008; Perini *et al.* 2011, 2013). For this reason, the structure is considered here as an intermediate design, neither a GF nor a LW. The planter boxes can be installed at different heights on the façade of buildings or rooted on the rooftop; with the vegetation cascading down or climbing up. They are sometimes called 'perimeter flowerpots', 'double-skin green façade' or 'planter box curtains' (Stec *et al.* 2005; Köhler 2008; Pérez *et al.* 2011a,b,c).

2.2.1.4 Masonry walls

Masonry walls can either be freestanding or retaining walls (Jim & Chen 2010b; Jim 2013). Usually used as boundary demarcation, they are composed of brick, stone, mortar or concrete. They are widely distributed in the urban ecosystem and are estimated to give one hectare of vertical surface for every ten hectares of horizontal street surface in densely built-up areas (Darlington 1981).

Masonry walls are built upwards, with successive rows of stones overlapping each other. The space between two rows is filled with smaller stones and sometimes with a capping stone bridging the top (Presland 2007). A distinction is made between dry stone walls and mortared walls that are usually more shaped with regularly rectangular stones held together by mortar (Jim 2013, see also section 2.3.2). While dry stone walls are usually only freestanding demarcation walls, mortared walls can be used as building, boundary, and retaining walls. Although they are man-made structures, masonry walls can be naturally colonized by vegetation and act as a natural transition between hedgerows and living walls (Chiquet *et al.* 2012).

Retaining walls, also called 'landscape walls', are usually slightly sloped rather than vertical (Le *et al.* 2013). They are typically structured of stacking material (e.g. poured concrete or concrete blocks, stacked railroad ties, plastic units) with room for growing media and plants. Their primary function is slope stabilisation as they bind soils between two different elevations.

Over time, vegetation will naturally cover masonry walls, primarily with plants like ferns, mosses and lichens (see also section 2.3.2). According to Payne (1978) and Grenville (1999), no fewer than 18 vascular species are specialists of masonry walls, including the well-known species *Asplenium marinum* sea spleenwort, *A. ruta-muraria* wall-rue, *Cymbalaria muralis* ivy-leaved toadflax, *Galium aparine and G. parisiense* wall bedstraw, *Geranium robertianum* herb robert; most of them are from rocky habitats. Trees (e.g. *Broussonetia papyrifera* paper mulberry, *Celtis sinensis* Chinese hackberry, *Ficus sp.*) can also easily colonise this habitat depending on the moisture degree, the habitat connectivity and the geographical location (Jim 2008; Jim & Chen 2010b). The flora colonising sloping masonry walls will be distinct to the one colonising vertical walls (Gilbert 1996) as the latter is a more challenging process due to the relative lack of ledges. Because the vegetation colonisation usually follows a natural process rather than being man-made, some authors do not include them in the concept of green walls (see Köhler 2008; Francis & Lorimer 2011).

2.2.1.5 Urban hedges

Urban hedges can be considered as part of the green wall concept as they are interchangeable with green façades or living walls for some of their features or ecosystem services (Chiquet *et al.* 2012). Historical features of the rural landscapes (Baudry *et al.* 2000), hedgerows are usually defined as linear structures of shrubs and/or trees managed in various ways (Baudry *et al.* 2000), whether planted or spontaneous (Burel 1996), that are most of the time interconnected into networks (Hinsley & Bellamy 2000). They can be composed of a wide range of deciduous or evergreen shrubs (e.g. *Corylus avellana* hazel, *Crataegus monogyna* hawthorn, *Rosa canina* dog rose, *Ulex europaeus* gorse) and trees (e.g. *Metasequoia glyptostroboides* dawn redwood, *Populus spp.* poplar) (see Burel 1996; Baudry *et al.* 2000). Historically they were thought to be planted as single-species stands (Hooper 1970); the selected plants depending on the available resources and the primary purpose(s) of the hedge (Pollard *et al.* 1974). They were at first used for fences or as sources of products such as firewood, timber or fenceposts (Baudry *et al.* 2000; Baudry & Bunce 2001; Tenbergen 2001). In urban areas, they are often planted along traffic corridors or around houses (Varshney & Mitra 1993) and there is little information on species used, their extent or their environmental values.

2.2.2 Short history of green walls; ecology, research and utilisation

Self-adhering climbing plants have been used on buildings for millennia (Lundholm 2006; Ottelé 2011). Around the Mediterranean, deciduous climbers were, and are, used for the shade they deliver in summer; whereas evergreen plants were used in the northern countries for the thermal insulation they provide on buildings (Köhler 2008; Ottelé 2011). Over the last two decades and mainly in Germany and North America, civic authorities and organizations realising the importance of plants for human well-being have established and promoted guidelines for green roofs (e.g. with *Sedum sp.*) and façades with climbers as part of urban development (Johnston & Newton 2004). As green façades and green roofs are relatively easy to construct, programmes (through legislation, tax incentives, compulsory measures), at the country or city levels, have been developed to encourage their utilisation (Table 2.1). Architects can for example integrate vegetation into construction as the outer façade element and an active building material (Johnston & Newton 2004; Perini *et al.* 2011). In some cities, green walls are now quite intensively used, for the greening of infrastructure, and as a mean to include biodiversity to the built environment. In Berlin for example between 1983 and 1997 (the duration of the incentive program) 245,584 m² of green façades were installed (in Köhler 2008). Green walls are seen as sustainable features for healthy, ecological and even 'biophilic' cities (Platt 2004; Beatley & Newman 2013). However, the type of green walls, the material used, its maintenance and durability will determine their effective sustainability and more information are needed on this subject (Ottelé 2011).

Since the early twentieth century in Germany, over 770 articles have been written on green façades according to Köhler (2008), with a peak in the 1980-90s. Three main categories appear (in abundance order): 'botanical research', 'gardening and technical aspects of landscaping on houses' and 'ecological functions' (Köhler 2008). Two PhDs (Bartfelder & Köhler 1987; Thönnessen 2002) were written on the latter category and a third focussed on GF's social and economic aspects (Chilla 2004); all three were written in German. Many articles were produced on the environmental values of green façades (see for example Minke & Witter 1982; Kiessl & Rath 1989; Köhler 1989a,b; Oger *et al.* 1992; Köhler *et al.* 1993; Thönnessen & Werner 1996; Schuldt *et al.* 2002) but unfortunately they were also written in German and furthermore published in regional or national journals, making them hard to access and apply in other parts of the world. Thus, although green façades are familiar to the public, scientific and technical information are yet to be fully established (Köhler 2008; Francis & Lorimer 2011).

In 1977, French researcher Patrick Blanc invented a new concept in green walls, based on the tropical aquatic plants he studied: plants can be rooted in an inert substrate at any height as long as nutrients are provided with water (Blanc 2008). This was the beginning of the felt-layer system (Blanc pers. comm.). Since 2008, the enthusiasm of the public for these new features launched a commercial market for green wall companies, and especially living walls (Blanc pers. comm.). When this present PhD project was begun in the year 2010, only a few commercial companies were working in this niche. Since then, many companies have appeared, offering different kinds of living wall systems. However, the lack of investment in research and development and the inherent constraints of the systems caused most of the new companies to fail. The first companies, which have been continuously developing their products and investigating the best plants for living walls are still present today. Following the development of urban ecology as a discipline (Breuste & Qureshi 2011), research on green walls found a new impetus (Köhler 2008). As such, Ottelé (2011), through a PhD project, investigated the value of greening façades for air pollution mitigation and for building physics (especially the insulation properties). Many research teams, currently working on green walls, were initially studying green roofs and transferred their research questions from a horizontal ecosystem to a vertical one (mainly on the basis of water for runoff management and on thermal insulation). However, most of the knowledge is not directly transferable from one ecosystem to the other and extensive studies are still needed (see also section 2.3).

Following the market development, a range of different LWS has been developed in recent years. In Europe, the Austrian, Dutch, English, French, German, and Spanish markets are now quite developed, as are the North American and North Asian markets (pers. obs.).

2.2.3 Commercial systems in the Northern Hemisphere

Some examples of the main green walls companies have been listed in Table 2.2 (information collected directly from the companies). It is interesting to note that despite the wide range of green walls and especially LWS, each country tends to use mainly between one and three systems (pers. obs.). In France, apart from Patrick Blanc's system using felt layers (Vertical Garden®), the main systems are: (i) metallic cages enclosing either *Sphagnum spp*. as rooting substrate (e.g. Green Wall®) or different mineral growing media (e.g. Inventae vert, Canevaflor®), sometimes covered with fleeces (e.g. Tracer); and (ii) plastic or aluminium modules (e.g. Modulogreen®, Soprema, Vertiss™). In Germany, climbers are mostly used through living curtains, direct and indirect green façades and green screens (e.g. Biotekt, Car Stahl GmbH, FassadenGrün), other systems involve freestanding planter boxes (e.g. Plant-Ed-Wall™ from Die Raumbegrüner GmbH) or aluminium gabion with mineral substrate (Optigrün®). The Netherlands has a broad range of living wall companies and the systems are mostly made of rockwool panels (like Mobilane® or Sempergreen®), substrate-filled metallic cage (e.g. Jonkers daktuinene BV), planter box racks (e.g. Greenwaves systems) or green concrete (e.g. Veluwe). In the UK, the commercial systems are mainly modular panels with preformed plastic modules (e.g. Scotscape, Treebox Ltd.) or rockwool units (e.g. Mobilane®), sometimes covered with polypropylene plastic fascia in front (e.g. Biotecture Ltd.). Originally based in Switzerland, Jakob® is one of the few companies specialising in green façades, offering stainless steel wires, rods, cables or mesh for climbing plant support and for creating a gap between the building surface and the vegetation. In North America, the main systems vary from felt-like system (e.g. Green over Grey™, Canada) to plastic modules (e.g. ELT Easy Green®, USA) and retaining walls (e.g. The Living Wall Company, USA). In Asia, many companies are currently expanding. Two of the main ones are Bin Fen (Taiwan) and Parabienta Green Living Wall (Japan), both with polypropylene (PP) modules. In Australia and New Zealand, Fytogreen and The Greenwall Company are among the main living wall companies.

Some of the LWS have been developed specifically for a mitigation effect of acoustic, thermal or particulate pollution (e.g. Canevaflor®, Tracer or Mobilane®). Other businesses came from the green roof industry, like Optigrün® or Sempergreen®. For some companies, like Novintiss™ or Soprema, LWS are just one part of their horticultural activities. Companies are sometimes installers and suppliers of systems produced by manufacturing companies, such as Jakob® operated in the UK by MMA Architectural Systems Ltd; whilst others have developed their own system of living wall but are also supplier and installer of another company's LWS. For example, The Living Wall Company in Canada developed a "retaining wall" concrete block but also installs a plastic module system from ELT Easy green, and

Scotscape, which installs the ANS Living Wall System™ among other systems, has also developed its own modular system. Companies with modular panels usually offer various sizes of their systems with or without adaptation for corners. Many of the living wall companies, after having developed their LWS, are now offering freestanding green screen products (as instant hedges or reusable hoarding) and indoor living wall systems (e.g. LivePicture® from Mobilane®).

The LWS found on these markets are significantly different (see also Table 2.6 in section 2.5) and this is reflected in the prices. Green façades are the cheapest system, £10-40/m² for direct greening and £30-100/m² with support (although prices will increase drastically with height - Mir 2011; Perini *et al.* 2011). Green screens are slightly more expensive (£100-200/m²) as they are usually designed with a built-in irrigation system (Farrell pers. comm.). Living curtains can be as cheap as an indirect greening system (although they require connections to an irrigation system) or much more expensive depending on the supporting structure: £50-500/m² (Mir 2011; Ottelé 2011). Living wall systems with plastic modules (usually HDPE) are around £300-900/m² (Crepieux 2011; Perini *et al.* 2011), with felt systems: £300-700/m² (Blanc pers. comm.; Crépieux 2011; Ottelé 2011), with rockwool systems £400-700/m² (Mir 2011), with sphagnum gabions £540-1000/m² (Leblond 2013), and with foam substrate £600-1000/m² (Ottelé 2011). The cost also depends on the building surface and height, location, aspect, connections, etc. For LWS, usually large features, a maintenance contract is typically required, approximately 8-10% of the initial price per year. It is obvious from these figures that LWS are much more expensive than GF (both direct and indirect greening systems) and living curtains. This is mainly due to the materials involved, the design complexity, and the set-up required (water irrigation system, electricity, etc.). Some manufacturers also claim their system to be more self-sufficient in nutrients than others (e.g. sphagnum systems compared to felt-layer systems), or more durable (e.g. felt-layer systems have a life expectancy of approximately 10 years, whilst plastic modules could last in excess of 50 years - Ottelé 2011). Because of their cost, these systems are mainly used by companies and organisations (Dunnett & Kingsbury 2008) for the 'green' message it sends (see section 1.1.1). In parallel, many amateurs have developed their own LWS, often based on the felt layered system, and are happily sharing their success and failures through DIY tutorials on online forums and websites (e.g. Le Narbonnais 2011; Matt 2010; Fern 2011). Some companies specialised in small LWS suitable for private households, with prices ranging from £140/m² to £260/m² without the plants (e.g. HDPE recyclable plastic set-up from ELT Easy Green®, Easiwall or minigarden®, flexible plastic pockets (individual or not) from WoollyPocket) with manual irrigation. In comparison, amateurs claim that their own LWS (usually felt-layer with built-in irrigation) usually cost around £50-100/m² without the plants (see previous references).

Green wall companies usually strongly advertise the benefits green walls provide and the following literature review will present the current state of scientific knowledge on their proven environmental values.

2.3 THE ENVIRONMENTAL VALUES OF GREEN WALLS

As a green infrastructure component, green walls have the potential to deliver many ecosystem services (Fig. 2.3). They have experienced a revived interest since the creation of the living wall systems approximately 25 years ago (Blanc 2008) and are now quite familiar in urban areas (Francis & Lorimer 2011). This literature review investigated the known characteristics and the quantified ecosystem services delivered by green walls. The aim was not to give an exhaustive knowledge on green walls but to investigate the different ecological values that have been surveyed and quantified (Fig. 2.3). Distinction was made between their shared characteristics and the specific attributes of each type of green wall. Whenever possible for a given value, existing studies on the different green walls (urban hedges, masonry walls, green façades (of whom green screens), living curtains and living walls) will be reported. If a type of green wall is not mention in a section, no studied were found on it. This review is partly based on a conference work arising from this PhD research (Chiquet *et al.* 2012) which looked at the analogy between urban green walls (focusing on green façades and living walls), rural masonry walls and rural hedgerows.

Green wall, as with any other green infrastructure, tends to create a semi-natural habitat when used in an urban environment (Dover 2006). Irrespective of their size, structure or vegetation composition, they provide visual amenity (Dover 2006). When free-standing, by structuring open areas they create intimacy (Crowe 1994); whilst against a wall, they have the ability to hide ugly features (Crowe 1994) or prevent damage such as graffiti (pers. obs.).

2.3.1 The specific use of hedges compared to other green walls

Compared to rural hedges, there is little information available on urban hedges. In rural areas, hedgerows have had a practical and functional value for centuries (Barr & Petit 2001). Since the beginning of the last century, they gradually started to lose their initial functions, due to changes in agricultural economics, and were soon threatened by lack of management or even uprooting (Baudry *et al.* 2000). In recent decades however, conservation research showed the ecological values of hedges, and restoration and planting have been supported in agri-environment programmes on regional or national scales (e.g. see ‘Code Wallon de l’Aménagement du Territoire, de l’Urbanisme et du Patrimoine 2004’ (Belgium), ‘Environmentally Sensitive Area and Countryside Stewardship Schemes 1987’ (Britain), ‘Grenelle de l’environnement 2007’ (France), ‘Federal Nature Conservation Act 1998’

(Germany), 'Hedgerows Regulation 1997' (UK), 'European Union Habitat Directive 1992' (Europe)).

Although they have been well studied (see Barr & Petit 2001), rural hedgerows are not easily defined in ecological terms as they have many different roles within and between different types of landscape (Baudry *et al.* 2000). Because of their structure they need space (a minimum of 0.5-1m wide depending on the species (Anonymous 2013b,c) and require a large rooting volume where other green walls do not necessarily need ground and can be quite narrow. In the countryside, these characteristics make them suitable for the function of windbreak (Burel 1996), control of soil erosion (Chaowen *et al.* 2007) and give them an important drainage role (Burel & Baudry 1995). After the decline of their traditional functions as boundaries or sources of products, novel functions have been highlighted, for example as reservoirs of biodiversity or historic landscape conservation (Burel & Baudry 1995; Baudry *et al.* 2000; Tenbergen 2001). Hedges are more appropriate for rural areas than other green walls because of their robustness and low cost (Burel 1996). They can act as corridor for movement and dispersal of many forest vertebrates and invertebrates species (McCollin *et al.*, 2000), provide shelter for the species feeding in the open land adjacent to them (Burel & Baudry 1990; Green *et al.* 1994; Hinsley & Bellamy 2000) and supply food resources for others groups (Maudsley 2000). Hedges maintain an essential habitat for specialist species or groups (e.g. *Emberiza cirlus* cirl bunting - Hinsley & Bellamy 2000; flying Diptera - Peng *et al.* 1992) or for species that have adapted to this ecosystem after the loss of their own refuge (e.g. *Perdix perdix* grey partridge - Green *et al.* 1994; see also Hinsley & Bellamy 2000). Different types of maintenance (especially concerning the cut) will affect the hedge structure and have an important effect on the hedge development. In Europe, most country/region would have a dominant type of hedge management (e.g. regional style of hedgelaying in UK, Blissett 2014), sometimes enforced by local regulations (e.g. 'Loi cantonale sur la protection de la nature' (Bern, Switzerland), 'Cahier des Charges Méthodologiques - Plan des Gestion des Haies' (Calvados, France), 'Règlement sur la conservation de la végétation arborée' (Geneve, Switzerland), 'Gestion raisonée des haies' (Poitou-Charantes, France)). This would contribute to the cultural character of each region (Baudry *et al.* 2000).

Due to their needed volume, the available spaces for new hedges in an established urban area are more limited than for some other green walls. They are usually planted around houses as a screen to provide privacy, to define boundaries, and for aesthetic purposes (Varshney & Mitra 1993). They are also used along traffic corridors in urban or suburban areas to serve as a windbreak (Bouvet *et al.* 2007; Steffens *et al.* 2012) or as a noise barrier (Kotzen 2004; Fuller *et al.* 2009; Steffens *et al.* 2012). They have significant functions of shading, lowering temperature, increasing humidity, modifying wind velocity and lowering noise (Kittas 1992;

Ning *et al.* 2002; Yaomin *et al.* 2006). For more details, see the following sections relative to each aspect.

2.3.2 Floral biodiversity of green walls

Much of the work related to masonry wall ecology is based on the flora naturally growing on old buildings, ruins, or boundary walls, in urban or agricultural areas (see Woodell & Rosseter 1959; Woodell 1979; Trocha *et al.* 2007; Pocock 2009), with records as early as 1660 in the UK (Rishbeth 1948). The ecology of masonry walls is often compared to that of rocky cliffs (Cooper 1997) as they share common features such as bare stone surfaces and scarcity of soil, humus and moisture (see Segal 1969; Larson *et al.* 2004; Lundholm & Marlin 2006). Despite being a harsh habitat with precarious anchorage, low nutrients supply and low moisture (Larson *et al.* 2004; Lundholm & Marlin 2006), a great variety of plant species can take root on walls (see also section 2.2.1.4). As such, 125 species of lichens and fungi and 66 species of higher plants were recorded on a Roman wall in Colchester, South-East England (Darlington 1981). Another survey in Hong Kong identified 30 species of trees on old masonry walls (Jim 1998). Most of the species found, usually unsown, are generalists with competitive functional strategies (Gilbert 1996; Jim 1998, 2013; Francis & Hoggart 2009).

Wall composition (e.g. bricks, stone, mortar) will vary in its physical features (e.g. porosity), chemical characteristics (e.g. pH) and rate of decomposition (Warscheid & Braams 2000). This will have an influence on the floral diversity (Francis 2010) and as such, a distinction is made between dry stone walls (sometimes called dry packed walls, with joints left unfilled) and mortared (filled) walls (Chan 1996; Presland 2007, 2008a,b; Jim 2013). In the latter, the mortar is a source of nutrients and water and provides an anchorage for roots and rhizomes resulting in a more diverse plant population than in dry stone walls (Presland 2008a). For example, 40 plant species were found in dry stone walls and approximately 50 species on mortared walls in Wiltshire, UK (Presland 2008b).

The supply of water and nutrients, the proximity of walls to adjacent natural ecosystems (for seed supply), the structure maintenance, and the habitat size are four key factors for mural vegetation (Jim & Chen 2010b). In urban areas, masonry walls can suffer strong and frequent anthropogenic disturbance (Aslan & Atamov 2006) which can reduce colonisation by vegetation and modify the botanical composition (Jim & Chen 2010b).

The extensive work on floristic inventories and plant diversity of masonry wall vegetation (Payne 1978; Francis 2010) either summarises extensive surveys of sites across Europe (Segal 1969; Darlington 1981), or investigates a very small geographical area like a town (e.g. Cambridge (Rishbeth 1948), Durham (Shimwell 2009)), a university campus (e.g. Lundholm & Marlin 2006) or even just a monument (e.g. Castillo de San Marcos (Zomlefer

& Giannasi 2005), Colosseum of Rome (Deakin 1855). Studies have been carried out in many countries (see examples in Table 2.3). However, there is a geographical bias in the literature on wall flora (Lundholm & Marlin 2006) as most studies are based in Europe, and only a few on the other continents. This can be explained by Europe's history of landscaping and urbanisation compared to the New World (Francis 2010).

The floral biodiversity of hedgerows was previously detailed and further explanations given in sections 2.2.1.5 and 2.3.1.

Green façades and living curtains support climbing plants and wall shrubs (Fitzgerald 1906; Squire 2005; Dunnett & Kingsbury 2008). As discussed in section 2.2.1.2, climbers show many ways of adhering to a surface (Appendix 3 and 4). Twining plants such as vines (e.g. *Wisteria sp.*, *Lonicera sp.* honeysuckle, *Jasmine sp.*) will twine their stems with a circular movement around the vertical support structure; the latter need to be able to support a heavy load (Jakob® 2003). Tendril climbers, either leaf-stem climbers (e.g. *Clematis sp.*) or leaf climbers (e.g. *Vitis sp.* grape vine) will develop special off-shoots to grab hold of the supporting structure (Dunnett & Kingsbury 2008). They are lighter than the vines, and as such, may not be suitable in high wind situations and may need grid-like or reticular support (Dunnett & Kingsbury 2008). Scrambling plants (e.g. *Bougainvillea sp.*, *Hardenbergia sp.*) will only use the trellis system to prop themselves, their upward growth being supported by their prickles and thorns (Jakob® 2003). Self-adhering climbers, either adhesive-suckers (e.g. *Parthenocissus tricuspidata* Japanese creeper) or root-climbers (e.g. *Hedera helix* English ivy), do not require auxiliary means of support (Jakob® 2003). Taking typically three to five years to be fully-established, climbers usually grow up to 5 or 6 metres high, although some species can reach 10 metres or even 25 meters high (Dunnett & Kingsbury 2008).

Compared to green façades and living curtains, living wall systems are not restricted to such a limited range of plant growth forms. They allow a greater variety of plants and offer a more creative potential in terms of design and aesthetic (Köhler 2008; Elinç *et al.* 2013; Appendix 2; section 2.2.1.1). The only restriction on a living wall will be the hardiness and the final weight of the plant in relation to the support structure (Dunnett & Kingsbury 2008).

2.3.3 A building bioprotection cover or a biodeteriorative role?

It is a common belief that climbers, especially ivy, will damage the building, ripping out mortar and encrusting in the joints with their roots, exploiting any block weakness (Johnston & Newton 2004; Viles *et al.* 2011; Sternberg *et al.* 2011), thus affecting the building integrity and increasing humidity. To establish the direct biological role of climbers, Sternberg *et al.* (2011) worked on the effects of a canopy of English ivy (*Hedera helix*) on historic buildings. Their research aim was to investigate whether it serves as a detrimental (biodestructive) or a beneficial (bioprotective) conservation strategy for historical walls (Viles pers. comm.) against agents of deterioration (frost, direct solar radiation, rainfall intensity, pollution, etc.). It appears that ivy can actually retard bio-deteriorative processes on walls through the creation of a more stable surface microclimate. It protects the walls from thermal expansion and contraction (i.e. freeze-thaw) and short-term moisture fluctuation (Sternberg *et al.* 2011). Similarly, soft capping, made of grass and other plants (plus soil), was found to provide a better protection, through thermal blanketing, than hard capping (Viles & Wood 2007; Lee *et al.* 2009). In addition, façades covered by a layer of vegetation would be drier than without, as the leaves will create a physical barrier against rainfall (Johnston & Newton 2004). Moreover, vegetation layers reduce the amount of UV light received by building materials (Grant & Heisler 1996). As UV light has been shown to deteriorate the material and mechanical properties of coatings (i.e. paints, plastics, etc.), presence of vegetation on buildings increases the materials' life-span and reduces the maintenance costs of the façade (see Perini *et al.* 2011). It appears that public opinion towards the damage caused by climbers has been exaggerated; although plants will accelerate the process of deterioration if decay is already present (Woodell 1979; Cathersides *et al.* 2010).

Green screens, and indirect greening systems, are usually set up few centimetres away from the building façades to avoid plants growing on the walls. In the case of living walls, no degradation is expected as the planted structure has rootproof and waterproof membranes between the planter modules and the walls (Blanc pers. comm.). The only risk of degradation would come from a leaking irrigation pipe (Farrell pers. comm.).

Nevertheless, despite this bioprotective role, it is important to consider several points before establishing a green wall (see Köhler *et al.* 1993; Dunnett & Kingsbury 2008; Perini *et al.* 2013): the final weight of the structure, the wall sturdiness and the final height of the plants. Ensuring the waterproofing of membranes in the case of LWS and special attention around window edges are important to avoid any leaks and corrosion. If the GW is not well designed and maintained, important damage can occur to the building, the vegetation and the supporting structures (Fig. 2.4). The maintenance will depend on the growing speed and the presence of constraining factors (such as windows, gutter or doors - Ottelé 2011).

2.3.4 Urban heat island reduction, thermal mitigation and energy saving

Several studies have shown the potential of green walls to mitigate the effects of the weather through thermal regulation of buildings and passive heat island reduction (Ottelé 2011). The mitigation is due to four mechanisms: (i) the ability of plants to intercept solar radiation through their shading (Stec *et al.* 2005; Jin *et al.* 2009; Kontoleon & Eumorfopoulou 2010), (ii) the thermal insulation provided on the first part by the vegetation, plus the substrate and structure in case of LWS (Hoyano 1988; Wong *et al.* 2010a), and on the second part by the air gap between the vegetated structure and the building (Jim & He 2011; Chen *et al.* 2013), (iii) the effect of evapotranspiration by plants that can extract heat from the surrounding air (Okinaka *et al.* 1994; Schmidt 2006, 2009; Miller *et al.* 2007), and (iv) the alteration of the wind effect (shelter) on the building (Ochoa 1999; Dinsdale *et al.* 2006; Perini *et al.* 2011).

The ability of plants to improve a building's microclimate focused at first on green façades, and more recently, on living wall systems. In the 1980's, one of the first studies by Hoyano (1988) looked at the use of climbers as solar control and established the inverse correlation between solar transmittance and ivy growth conditions; thus highlighting the potential use of green walls for thermal insulation. Experimental and simulation studies have mainly been carried out in the Mediterranean area (e.g. Holm 1989; Kontoleon & Eumorfopoulou 2010; Pérez *et al.* 2011a; Larcher *et al.* 2013; Mazzali *et al.* 2013; Perini *et al.* 2013) or in a tropical climate (see Wong *et al.* 2009, 2010a; Jim & He 2011; Chen *et al.* 2013). The main aim has usually been to establish how green walls could assist in cooling buildings in summer rather than reducing heat loss in winter.

The coverage density play an important role in the thermal mitigation as the outer layers were shown to act as optical filters while the deeper layers act as an insulation material (Eumorfopoulou & Kontoleon 2009). For example, Ip *et al.* (2010) showed that one layer of leaves of *Parthenocissus quiquefolia* Virginia creeper can reduce solar radiation by 37% and five layers can reduce up to 86%. On living walls, the cooling effect of vegetation is enhanced by the type of systems (its insulation value and substrate types, see Wong *et al.* 2010a; Mazzali *et al.* 2013), making them more efficient than GF (Wong *et al.* 2010a). The effective shading of green wall lowers heat absorption of the building façades and therefore lowers indoor temperature (Hoyano 1988). This can result in a modification of indoor air temperature (in the room directly behind the GW) by 7°C (Bartfelder & Köhler 1987; Hoyano 1988; Okinaka *et al.* 1994). When plants are installed instead of blinds in front of windows, the cavity air temperature between the shading feature and the window glass has been shown to be twice as low behind plants than as behind blinds (Stec *et al.* 2005), affecting the heat transfer through the façade. Shading through vegetation will also affect the indoor relative humidity (Ip *et al.* 2010), increasing it by 5-14% during the hotter months (from July to October) (Miller *et al.* 2007).

LWS and GF, either free-standing or against a building, were shown to provide a significant cooling effect on the building surface, modifying the external temperature by 2-6°C (Cheng *et al.* 2010; Kontoleon & Eumorfopoulou 2010; Wong *et al.* 2010a) depending on the air circulation (Wong *et al.* 2010a), and especially in the summer (Eumorfopoulou & Kontoleon 2009). For example, during sunny days, the external surface temperature difference between a bare wall and its equivalent living wall with preformed plastic modules can be up to 12°C; whilst the difference can be up to 20°C with a felt-layer system (Mazzali *et al.* 2013). Through their freestanding status, urban hedges were studied more for their thermal mitigation effect on the microclimate of the street canyon than the thermal insulation of building. As with other GW, they were shown to have significant functions of shading, lowering temperature, increasing humidity and modifying wind velocity (Kittas 1992; Ning *et al.* 2002; Yaomin *et al.* 2006). Although they have been less investigated than GF and LW, hedges (shrub cover, or tree and shrub cover) were shown to reduce temperatures in a built environment by at least 1°C (Giridharan *et al.* 2008). Through the mitigation of the external temperatures, GW can have a significant effect on the Urban Heat Island (UHI) (Okinaka *et al.* 1994), as the latter can cause air temperature to be 2-5°C higher than the average (Taha 1997; Onishi *et al.* 2010).

The efficiency of GW for heat transfer mitigation will depend on the type of plant species and on the rooting media (Mazzali *et al.* 2013); e.g. mulch (in the case of hedges and GF) reradiate more energy than other media like turf (Montague *et al.* 1998). The effect of GW on the indoor and outdoor microclimate, mostly effective in daytime (Mazzali *et al.* 2013; Tan *et al.* 2013), is dependent on the altitude (Giridharan *et al.* 2008; Wong *et al.* 2010a), the human density (Giridharan *et al.* 2008) and the percentage of vegetation (above 44% for Zhu *et al.* (2011), above 60% according to Liu *et al.* (2008)). Due to the complexity of thermo-dynamic transmission processes, studies of green walls have usually focused on the development of computer models, e.g. exploring the effect of a vertical greening system on a building and in a street canyon (see Zaiyi & Niu 1998; Stec *et al.* 2005; Wong *et al.* 2009; Susorova *et al.* 2013). They showed that the value of green walls for thermal mitigation will depend on its locality, climatic elements and wall aspect (see McPherson *et al.* 1988; Holm 1989; Jim & He 2011), but that the leaf density and the Leaf Area Index (LAI), which affects the amount of shade produced and the level of evapotranspiration, are also important (see Jim & He 2011; Rutgers 2012).

The shading of GW reduce solar gains and heat flow into the building through passive cooling (Wong *et al.* 2009, 2010) and can reduce the electric consumption of cooling systems by 20% (Stec *et al.* 2005). Green façades are a better solar control on west-facing walls compared to east-, equator facing- or pole-facing walls; and are more efficient on equator-facing walls compared to pole-facing walls (McPherson 1988; Okinaka *et al.* 1994; Jim & He 2011). For example, on a west-facing wall, well-established ivy reduces heat flux through the external walls by 75% (Hoyano 1988) and the peak-cooling load (i.e. rate at which heat is removed from a conditioned space to maintain a constant space air temperature) by 28% (Di & Wang 1999). In addition, green walls were shown to be able to decrease heat flow losses and hence improve the energy efficiency of buildings (Zaiyi & Niu 1998; Eumorfopoulou & Kontoleon 2009; Wong *et al.* 2009). Through a computer simulation, dense and evergreen vegetation in front of all surfaces of a building has been shown to reduce the annual space-cooling costs by 53-61% and peak cooling loads by 31-49% in temperate and hot climates, but to increase the annual heating cost by 21% in cold climate (McPherson *et al.* 1988). Unlike LWS, green façades, living curtains and hedges can use deciduous plants to offer seasonal regulation of shading in cold climate (Hoyano 1988; Ip *et al.* 2010). The dense foliage in summer will protect the building by its shading effect (Ip *et al.* 2010), whereas the lack of leaves in winter will allow solar radiation to be absorbed by the building façade or to penetrate through the windows (Johnston & Newton 2004; Kontoleon & Eumorfopoulou 2010); hence reducing the energy consumption of the building for heating and air-conditioning. A computer simulation, specifically developed to simulate the thermal effects of deciduous and evergreen vegetation cover on exterior walls (Holm 1989), showed that, for a building, the presence of deciduous foliage on the equator-facing walls and evergreen foliage on the other walls can reduce or even obviate the need for artificial heating or cooling in hot-arid climates.

Depending on its design, a green wall can either increase the need (and therefore the cost) for cooling and heating or reduce it (McPherson *et al.* 1988; Wong *et al.* 2009). However, the more a building is insulated, the less a vertical greening system will have a significant effect on the heat loss (Kontoleon & Eumorfopoulou 2010), although it will still have an effect on solar radiation, wind velocity and shading.

2.3.5 Air quality improvement

Previous literature showed the value of vegetation for improving the air quality through particulate removal. Subsequently, green walls, as other vegetated elements, were investigated for their potential role in reducing air pollution in urban area. Particulate matter (PM) consists of microscopic particles of solid or liquid suspended in the air, coming mainly from road transport (Rai & Kulshreshtha 2006; Elbir *et al.* 2010). They are regulated based on their size (Cheung *et al.* 2011); and specific attention is drawn toward PM_{10} (particles less than 10 µm in aerodynamic diameter) and $PM_{2.5}$ (particles less than 2.5 µm in aerodynamic diameter) because of their impact on human health (Orru *et al.* 2010). The dust-filtering ability of plants (Fig. 2.5 and 2.6) is directly correlated with the characteristics of the foliar surface: the size (LAI), the hair density on the leaves and the quantity of epicuticular waxes (Kulshreshtha *et al.* 2009; Sæbø *et al.* 2012). Therefore, studies were carried out on the individual effect of different plant species on particulate pollution (see Ottelé 2011; Dzierżanowski *et al.* 2011) without considering the impact of having plants set on a vertical surface. As such, tree and shrub species were often investigated for their mitigation values in urban areas (e.g. Das 1986; McPherson *et al.* 1998; Gautam *et al.*l 2005; Chakre 2006; Fuller *et al.* 2009; Qiu *et al.* 2009; Dzierżanowski *et al.* 2011; Hofman *et al.* 2012).

With a large collecting surface area, green walls can potentially play a substantial role in reducing air pollution, especially as they promote vertical transport by enhancing turbulence

(Thönnessen & Werner 1996; Van Bohemen *et al.* 2008). Only few authors investigated the value of hedgerows for reducing particulate pollution, usually along busy roads, and mainly in Indian and Chinese cities. Direct comparison is difficult due to variations between the variables studied. By assessing the particulate abatement capacity (PAC), Varshney & Mitra (1993) found that hedgerows can provide an efficient barrier against road dust and can reduce particulate matter (all sizes combined) by 30% to 50%. Lin *et al.* (2011) showed that the removal of concentrations of total suspended particulate (TSP) and PM_{10} by hedges could be up to 40-50%. The efficiency of vegetation to mitigate particulate pollution appears to depend on the density of planting, the plant canopy density, porosity and size (Varshney & Mitra 1993; Shan *et al.* 2007; Lin *et al.* 2011). As such, shrubs and hedges appear to be more efficient than trees (especially conifer) for dust-retention (Chen *et al.* 2006); and differences have been established between different shrubs species. *Duranta plumieri* was proven to be more efficient at capturing particulates than *Nerium indicum* and *Bougainvillea spectabilis* (Varshney & Mitra 1993) and *Terminalia arjuna* seemed to be more efficient than *Cassia fistula*, *Bougainvillea* 'Mahara', and *Polyalthia longifolia* (in increasing order, according to Kulshreshtha *et al.* 2009). These results appear to be comparable in number to the one obtained in a rural area where a hawthorn hedge (*Crataegus sp.*) was shown to filter PM_{10} by up to 34% from ambient air (Tiwary *et al.* 2008).

The trapped particles are usually indicators of nearby traffic roads or industrial plants (Ottelé 2011; Sternberg *et al.* 2010); and as such, they are a good representation of localised pollution (Fumagalli *et al.* 2010; Sæbø *et al.* 2012). Thus, not only is the size of the trapped particulates of great interest; their chemical composition is also important. Their primary components are usually sodium chloride, carbon (organic and elemental), trace metals and mineral components; their secondary components would be sulphate (SOx), nitrous oxides (NOx) and water (Fauser 1999; Anonymous 2005). The presence in PM of heavy metals, polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs) has been linked with respiratory and cardiovascular illness (see Brunekreef & Holgate 2002; Anonymous 2005). A green façade may be a relatively easy way to improve the air quality as climbers like *P. tricuspidata* are passive accumulators of heavy metal aerosol pollutants (Thönnessen & Werner 1996, see Fig. 2.6).

The dust particles mainly adhere to the outside of the vegetation (Ottelé 2011; Sternberg *et al.* 2010). Ivy plants for example mainly trap particles inferior to 1.5 µm on the upper side of the leaves (Ottelé *et al.* 2010; Sternberg *et al.* 2010, Fig. 2.5). As plants are subjected to repeated wind and rain events, a portion of pollutants will be regularly washed off the leaves, either hitting other surfaces or infiltrating the ground (Martuzevicius & Kliucininkas 2011; Sæbø *et al.* 2012) allowing new particles to be trapped by the plants (in a continuous and somewhat complex process that is yet to be fully understand).

Due to the aerodynamic complexity of the distribution of particulates, studies typically use computer simulations to explore the effect of vegetation barriers on particulate pollution (see Tiwary *et al.* 2005; Bouvet *et al.* 2007; Currie & Bass 2008; Hofman *et al.* 2012; Steffens *et al.* 2012) and more experimental studies are therefore needed. For living walls and green façades, more work is required to evaluate to what extent existing knowledge on plant species' ability to trap particulates at the ground level or on trees is transferable to the wall context. Additional studies are also needed to investigate the effect of long-term accumulation of PM on the morphology and physiology of plants. As such, near pollution sources, modifications of leaf surface characters have been observed: increased frequency of epidermal cells, stomata and trichomes, erosion of waxes, and clogged, slightly risen stomata (Kupcinskiene & Huttunen 2005; Rai & Kulshreshtha 2006; Rai *et al.* 2010). This suggests the importance of evaluating the plant species' tolerance to pollutants in urban areas (Sæbø *et al.* 2012). According to Helmers *et al.* (1998), Rai & Kulshreshtha (2006), Qiu *et al.* (2009), to look at the plant responses to air pollution, a distinction has to be made between organic compounds (OCs), oxides of nitrogen (NOx), sulphur dioxide (SO_2), suspended particulate matter (SPM), heavy metals (Cd, Co, Cu, Zn, Pb, Pd, Pt, etc.), and inert dust.

The ability of plants and growing media to trap dust has two opposite human health contexts. First, plants improve the air quality by reducing particulate pollution and therefore can have great health improvement effects. Secondly, it also means that in urban areas, it is necessary to obtain metal analyses prior selecting locations for growing edible plants (Sterrett *et al.* 1996) such as on a vertical garden.

2.3.6 Noise attenuation

Noise pollution, especially along road corridors, is a major issue in urbanised areas for human health and social costs (den Boer & Schroten 2007). Plants (especially leaves and stems) scatter high frequency sound waves (Aylor 1971; Pal *et al.* 2000), which have been shown to have significant effect on human health (Berrien 1946). Noise reduction properties of vegetation have been extensively researched on the ground. The effectiveness of sound attenuation have been shown to depend on the plant species, and the width, height, density and LAI of vegetation (e.g. Aylor 1972; Ayaz & Arshad 1998; Fare & Clatterbuck 1998; Pal *et al.* 2000; Pathak *et al.* 2008; Van Renterghem *et al.* 2012; Tyagi *et al.* 2013), and the sound frequencies (Pal *et al.* 2000; Pathak *et al.* 2008; Tyagi *et al.* 2013).

Along with green roofs (see Dunnett & Kingsbury 2008; Van Renterghem & Botteldooren 2009; Yang *et al.* 2012), green walls have been investigated for their acoustic effect. Plant species, substrate, and the trapped layer of air between plants and the building surface can be expected to work as acoustic insulation by absorption, reflection and deflection (Dunnett &

Kingsbury 2008). However, due to their relative novelty, research on the acoustic performance of green walls is almost non-existent (Wong *et al.* 2010b).

Some commercial living wall systems have been developed specifically for this purpose (such as the 'mur végétalisé antibruit' from Canevaflor® and the ' vertiflore' from Tracer, see also section 2.2.3). Wong *et al.* (2010b) investigated different types of green façades and living walls in HortPark, Singapore. Although results were drawn from only one replicate of each GW type, at least four points were noticeable. When vegetation is sparse and leaves a large surface of the wall exposed to sound (e.g. a young green façade or some living curtains), it is necessary to use plants with fairly good acoustical absorptive properties to have any effect on the acoustic insulation. The presence of an air space between the green wall and the building surface has a significant impact on noise transmission, with an insertion loss up to 7.0 dB which is 'clearly noticeable' to human ears. LWS with a substantial volume of substrate will be more effective at reducing low frequency noise sources than a system with little or no substrate. Even the GW with the lowest acoustic reduction made a change perceptible to human ears.

Urban hedges were shown to have significant effect at lowering noise (Samara & Tsitsoni 2011), especially when composed of both shrubs and trees for to their multi-layered structure (Ayaz & Arshad 1998; Pal *et al.* 2000; Yaomin *et al.* 2006; Van Renterghem *et al.* 2012). In an attempt to reduce acoustic pollution, inert noise barriers have become ubiquitous features along busy roads (den Boer & Schroten 2007). Their integration into their surroundings and their efficiency appear to be enhanced by the presence of vegetation that is often naturally colonising (Kotzen 2004; Baldauf *et al.* 2008). Due to their strategic location, noise protection walls especially when covered with vegetation, either naturally e.g. by ivy (Ottelé 2011), or on purpose e.g. by moss (Gorbachevskaya & Schreiter 2013), are often studied for the retention capacity of particulate matter (Baldauf *et al.* 2008).

In addition to the effective acoustic mitigation, the presence of vegetation as a psychological factor on noise pollution should not be underestimated. Vegetation strips like hedges, even too sparse to have a significant impact on sound transmission can be perceived as efficient for noise reduction (Aylor 1977; Anderson *et al.* 1984).

2.3.7 Stormwater management

Green roofs have been extensively studied for their contribution to urban hydrology as they can mitigate and delay sudden discharges of stormwater to the sewage system (see Kruuse af Verchou 2005; Gobel *et al.* 2007; Simmons *et al.* 2008; Spolek 2008; Bates *et al.* 2013) and work efficiently as SUDs (Johnston & Newton 2004; Jaffe *et al.* 2010). A similar action, through interception of rainfall, can be expected from green walls. They are said to have the potential to diminish the speed and quantity of water runoff (Roehr & Laurenz 2008a; Francis & Lorimer

2011), and to prevent uneven stream flow (Dover 2006). As such, living curtains in Germany have been shown to evaporate about 1 m^3 of rainwater during summer months (the climbers were planted in planter boxes of nearly 1 m^2 by 40 cm deep) thus significantly reducing the water run-off (Köhler 2007). *Wisteria sinensis* appears to be the most effective in species tested so far in evaporating rainfall (up to 420 L/day, according to Dunnett & Kingsbury 2008). At the time of writing, no other studies of rainwater management by green walls have been found in the English scientific literature.

2.3.8 Economic, social and health aspects

The environmental values of green walls described above operate at the building and neighbourhood scales (Perini *et al.* 2011; Virtudes & Manso 2012) and they can all be linked with economic benefits:

- By lessening the impact of weather, plants can reduce the maintenance costs involved with maintaining building façades and increase their life-span (e.g. via protection against UV light that deteriorates material - see section 2.3.3).
- Energy savings due to green walls can be substantial. Protecting a house from wind can cut the heating demand by 25%. Likewise reducing the solar gain by 1°C reduces the energy consumption for air-conditioning 2.80% (Peck *et al.* 1999). The presence of a green wall could save up to 11% of annual heating cost per year according to McPherson *et al.* (1988); making the economic benefits key to encourage the use of GW on building (Perini & Magliocco 2012), see also section 2.3.4).
- The US EPA (United State Environmental Protection Agency) estimates that $PM_{2.5}$ kills 20,000 people and hospitalizes many more each year in the US (Arnett 2006). In parallel, air pollution from roads is estimated to cost the EU approximately 100€ billion a year in health costs and environmental damage, with 100 million sick days and 350 000 premature deaths per year (Anonymous 2001). Reducing air pollution is consequently an urgent health issue in addition of being an environmental problem.
- In Europe, the costs of road traffic and rail noise are estimated to be in the range of 30-46€ and 2.3-2.5€ billion per year respectively, i.e. approximately 0.4% and 0.02% of total European GDP (den Boer & Schroten 2007).
- Limiting the quantity of rainfall can help to reduce the need and therefore the extent of storm water drainage infrastructure.

By providing visual contrast and relief from the built-environment, green walls can add value to a property but also help earn additional LEED® credits (i.e. an American rating system and certification for measuring buildings sustainability) in North America (Anonymous 2009b). The public is generally in favour of having more hedgerows (more for its nostalgic value than for its ecological impact - Baudry *et al.* 2000) and living façades (for their aesthetic value, novelty and the 'green' it brings to cities - Baudry *et al.* 2000; Dunnett & Kingsbury 2008); while green façades set off more ambivalent reactions (pers. obs.). Hedges and green screens can help shape social interactions by providing intimate social spaces but also allowing isolation if desired. They can reduce unwanted interactions through improved design of space; thus reducing crowding stress that has been shown to be highly detrimental in areas of dense urbanisation (see Calhoun 1962, 1971; Freedman 1975; Paulus 1988). The presence of green walls can also be expected to reduce anti-social behaviour (see also section 2.1.1). Adding seasonal indicators (e.g. blossoming, autumnal colour change) to buildings and streets, while hiding ugly infrastructure, helps improve the landscape of our cities.

Physical, and even visual, contact with plants can have direct health benefits (see section 2.1.1). Due to our complex relationship with the natural environment (Shwartz *et al.* 2012), green building designers are encouraged to incorporate green walls in their construction as part of a sustainable design strategy (Loh 2008; Köhler 2008). Aylor (1977) and Anderson *et al.* (1984) showed the psychological aspects of noise attenuation by vegetation such as hedges (see section 2.3.6). Probably because of the complexity of quantifying the value of green walls for human wellbeing and the release of stress, to date no manipulative studies have been done on this subject.

2.4 ENHANCING ANIMAL HABITAT IN URBAN AREAS

Urban areas are typically dense built-environments and include a wide range of manufactured structures: hard surfaces (e.g. pavements, roads, car parks), buildings (industrial, commercial and domestic), bridges, tunnels, etc. A substantial portion of the land will be covered with impervious surfaces, either structures or road pavement. Despite this artificial setting, the abundance and richness of wildlife in urban areas is not to be underestimated (Adams & Lindsey 2009; Shwartz *et al.* 2012). Cities are now home to a wide range of animals both invertebrate and vertebrate (Angold *et al.* 2006), as they can offer a wide range of habitats (Gilbert 1989; Carr *et al.* 1993).

2.4.1 Theoretical context: different approaches for biodiversity conservation and landscape ecology

The conservation of biological diversity has become a global concern (Anonymous 1992). Although not everybody agrees on the extent and significance of current extinctions, most governments consider biodiversity essential to underpin the functioning of the ecosystems on which we depend for food, fresh water, and health (Anonymous 2010c). In 1992, the international community undertook a commitment to slow the loss of biodiversity before the end of 2010 as part of the Convention of Biological Diversity (CBD) (Anonymous 1992). However, this target was not met (see Asher *et al.* 2010) and a new strategic plan (CBD 2011-2020, see Anonymous 2010c) was formulated with a vision for 2050. The new targets aim to integrate society more closely through participatory planning and knowledge building, and to address the different issues in a sustainable approach. In parallel, the concept of "biodiversity management" has been developed, over the last 30 years, to address the increasingly negative effect of the impact of humans on their environment (see Reid & Miller 1989; Schaltegger & Beständig 2012). The management of biodiversity has two main goals: the conservation of habitats, species, and genetic variability in such a way that it also delivers tangible benefits to human communities (Anonymous 2007). Similarly, the concept of "reconciliation ecology" emerged a decade ago (Rosenzweig 2003a,b), proposing a 'third' strategy of conservation (along with 'reserve establishment' and 'ecological restoration', see Dobson *et al.* (1997); Redford & Richter (1999); Rosenzweig (2003a,b)). In this approach, the anthropogenic environment is to be modified in such a way that it encourages non-human use and supports a greater range of species without compromising the societal utilisation (Francis & Lorimer 2011). The 'reconciliation ecology' does not set aside land for 'ecological uses' ('reserve') nor attempt to re-create a previous ecosystem state ('restoration') (Francis & Hoggart 2009; Francis & Lorimer 2011) but challenge the use of urban feature by both human and non-human. This attitude is opposite to the general belief that urbanisation is contradictory with, or detrimental, to nature (McKinney 2002). As such, current research on the sustainability of cities has favoured the restoration, preservation, enhancement and conservation of greenery and biodiversity in the urban context (Savard *et al.* 2000; Whitford *et al.* 2001).

2.4.2 The importance of spatial context, heterogeneity and habitat concept in the study of green walls

Recent work in urban ecology has highlighted the importance of using different approaches to study the urban fauna (Table 2.4): (i) the scale can be set at the landscape level or at the organism level, (ii) the focus can be on specific species or on communities assemblages, and (iii) a new green component can be looked at as a single ecosystem or as part of a more important network. Urban biodiversity studies usually include (i) work on the urban-rural gradient, (ii) surveys to quantify variation between cities, (iii) surveys of green infrastructure components, such as brownfields, green roofs, masonry walls, riparian landscape elements, street trees, or enclosed green spaces such as private gardens and parks, (iv) monitoring of the influence of native vs. non-native species, and (v) investigation of the incidence of urban pests. They usually survey a wide range of taxa including plants, invertebrates and/or vertebrates, especially mammals (e.g. bats, small rodents) and birds (Table 2.4).

The size of green components tends to follow a rural-to-urban gradient with large green spaces found often at the periphery of the city and the majority of green components within the city being small, i.e. under 100 m^2 (Gaston *et al.* 2013). Most species richness (e.g. birds, mammals, reptiles, amphibians, invertebrates, plants) tends to decrease in extremely urbanised areas, following a similar rural-to-urban gradient (McKinney 2008; Peach *et al.* 2008; Garaffa *et al.* 2009; Gagné & Fahrig 2011). Conversely, cities can be hot spots of plant species richness (Kowarik 2011). Both effects (urban-rural gradient and hotspot) can be linked with non-native species, human disturbance, species mobility and especially spatial heterogeneity, (McKinney 2008; Kowarik 2011).

The habitat heterogeneity is commonly high between the different urban green components and is influenced foremost by the way city-dwellers use them (Gaston *et al.* 2013). As such, the 'science of urban (landscape) ecology' considers the cities as 'spatially heterogeneous landscapes composed of multiple interacting patches' (Wu 2008, Niemelä 2014). By creating a green network of green infrastructure components such as green walls, a range of different biotopes will provide a successful territory for animal taxa in the urban environment (Snep *et al.* 2006). Moreover, the link with the direct environment of the town is not to underestimate either as peri-urban nature areas have been shown to have a positive influence on the presence of fauna in the inner-city (Kowarik 2011).

When studied, the inclusion of green walls in the wider context of the green infrastructure network and in the overall urban ecology is of importance due to the concept of habitat. A common view of habitats is that all resources required by a species are provided in a single individual space. However, in reality, this is unlikely to be the case as only some resources may be available in any given 'habitat patch'. This availability may also vary in quality and in quantity between two identical 'habitat patches' and may change over time (Dennis 2010). Habitat may then be defined as "the collection of resources that ensures the persistence of a population at a site" (Dennis 2010). As such, the use of a GW by animals may depend on the resources provided by the wall and on the animal species' particular needs. Some animal species may live and depend entirely on a green wall as their exclusive habitat; whereas for some the green wall will be only one component of their habitat and they may use it only for a specific resource (e.g. roosting, nectar and pollen sources, etc.),. This may particularly depend on whether the resources provided by the green wall are substitutable or non-substitutable with the additional resources provided by other green infrastructure components, spatially separated but still in proximity to each other, according to the complementation-supplementation theory (see Dunning *et al.* 1992; Ouin *et al.* 2004).

2.4.3 Animal specialisation to the urban environment

Many animal species have adapted to man-made structures and can now be seen as urban specialists (Adams & Lindsey 2009). For example, birds such as *Turdus merula* blackbird, *Parus major* great tit, *Columba livia* rock dove, *Hirundo rustica* swallows, and *Apus apus* swifts can use buildings instead of their traditional cliff or forest habitats and are found in cities in most latitudes (Evans *et al.* 2009; Sacco *et al.* 2013; Wang *et al.* 2013). Open-adapted bat species with low-medium frequency echolocation (e.g. *Nyctalus noctula*, *Pipistrellus spp.*) are likely to favour urban areas compared to clutter-adapted species with high or linear frequency echolocation (e.g. *Myotis myotis*, *Carollia perspicillata* - Threlfall *et al.* 2011). Some species, such as rats (*Ratus spp*.) or cockroaches (orders Blattaria and Blattodea), are regarded as pests, and attempts are made to control them (e.g. Morzillo & Schwartz 2011). However, most species are welcomed by the public and do not cause damage or disturbance. The built environment can even host rare and uncommon species such as *Phoenicurus ochruros* black redstart (Passeriformes: Muscicapidae), *Athous campyloides*, (Coleoptera: Elateridae), *Microlestes minutus* (Coleoptera: Carabidae), *Hippodamia variegata* (Coleoptera: Coccinellidae), and *Pardosa agrestis* (Araneae: Lycosidae) (Kadas 2006; Kowarik 2011). Implanting green walls in the urban environment is likely to create an additional habitat and we are yet to find out if they can harbour specialised, rare or endangered species.

2.4.4 Encountering nature in the built-environment

Conserving and enhancing natural ecosystems in cities is increasingly important given rising levels of global urbanisation: half of the human population is estimated to be living in urban areas and the proportion is expected to rise to 67.2% by 2050 (Heiling 2012). Urban biodiversity is directly influenced by the planning, design, and management of the built environment (Adams & Lindsey 2009). As such, the introduction and conservation of green infrastructure components (green walls, parks, hedges, tree lines, green roofs, etc.) provide an opportunity to improve the ecological functionality of urban areas (Dover 2006). These components have the potential to enhance biodiversity in urban areas (Hostetler *et al.* 2011) which has been shown to have measurable human benefits, both physical and psychological (Fuller *et al.* 2007).

Moreover, with most of the world's population living in urban areas, the exposure to nature grows increasingly restricted (Crane & Kinzig 2005) and city-dwellers are becoming unfamiliar with natural environments (McKinney 2006). Most human interactions with biodiversity are likely to happen within the built-environment (Kowarik 2011; Hennig & Ghazoul 2011) and providing opportunities for such interactions needs to be enhanced by the structure and the composition of the urban environment (Savard *et al.* 2000).

Faunal distribution, abundance and species richness are affected by the underlying resources (e.g. protection, food sources, ovoposition sites) made available to them in any given environment by the vegetation cover (see for example Maudsley *et al.* 2002 and Saunders *et al.* 2013 (invertebrates), Loyola & Martins 2008 (Hymenoptera), Stagoll *et al.* 2010 (bird), Sasal *et al.* 2010 (Coleoptera)). Most studies come from an essentially horizontal perspective, e.g. from traditional green spaces such as park and forest ground. As plants around and on buildings can be seen as an acceptable alternative habitat for wildlife (Sheweka & Magdy 2011), it is important to investigate new ways of greening our cities.

2.5 CONCLUSION ON THE LITERATURE REVIEWS ON GREEN WALLS AND URBAN WILDLIFE

2.5.1 Principal differences of the major green wall systems

Within green walls (see definitions in section 2.2.1), three major differences arise: (i) the type of foliage and botanical composition (see also section 2.3.2), (ii) the position of the growing media and (iii) the maintenance interventions.

When evergreen, GW may be used throughout the year by several animal taxa. Conversely, the animal biodiversity may be expected to be low in deciduous foliage during the cold months, although some overwintering niches may remain. Green façades and living curtains are made of climbing plants (or wall shrubs for GF) that can be evergreen or deciduous (sections 2.2.1.2-3). In the latter case, they display different features throughout the year, with the GW almost disappearing in winter (apart for the artificial support and/or the trunk and branches if any). This attribute may be useful as it will shade equator-facing walls in summer but, by shedding leaves, will facilitate solar gain in winter (section 2.3.4). In temperate climates, 30 to 50 plant species are suitable for green façades and living curtains (see examples in Appendix 3, Dunnett & Kingsbury 2008). On masonry walls, plant colonisation usually results without human intervention and is therefore limited to the local seed pool (section 2.2.1.4). The plants can be deciduous or evergreen (Jim & Chen 2010) and are mostly grass and ferns, although 18 vascular species were shown to be masonry walls specialist (Payne 1978). LW are completely man-made structures, mostly, or only, planted with evergreen foliage for aesthetic reasons; nevertheless, nearly any type of plants can be grown on them (see examples in Appendix 2, section 2.2.1.1, Francis 2010). Hedges can be deciduous or evergreen shrubs and/or trees (Baudry *et al.* 2000), the plant species usually being restricted to the geographical area and landscape structure (section 2.2.1.5, Burel 1992).

The presence of growing media results in a high degree of moisture and the presence of litter. These factors create an environment which has been shown to influence arthropod communities (Uetz *et al.* 1991; Maudsley 2000; Szybiak & Błoszyk 2009; Clergeau *et al.* 2011).

Green façades and hedges only have growing media at their base, whereas it is found at different heights on living curtains. On living walls and masonry walls, the growing media is present throughout the vertical surface, either evenly (living walls) or sporadically (masonry walls). Additionally, different designs of LW expose different areas of growing media, depending on their construction and hence influence the maximal plant density that can be grown per unit area. The volume of growing media on LWS can be (i) reduced as on the felt-layer system where only a little, if any, of growing media remains around the roots, or (ii) substantial, as on the angled plastic module system almost exclusively composed of growing media. LWS typically will have dripping line irrigation systems installed at regular intervals to ensure even delivery of water and nutrients whilst living curtains and green screens may also require irrigation, usually delivered at the base for green screens, and directly to the planter boxes of living curtains. Irrigation is typically rare for masonry walls and most green façades. As such, LWS will have more humid conditions associated with their foliage than GF.

Maintenance is carried out in various ways on the different types of green wall. Masonry walls usually remain untouched apart from the removal of tree seedlings (Jim 2013). On GF, maintenance is often limited to a cut twice or three times a year, to prevent the plants from blocking windows or gutters; this trimming can be in terms of height or both height and depth (pers. obs.). Similarly, hedges are trimmed in height and depth 2-3 times a year, especially in urban areas where they are usually kept relatively narrow due to space restrictions. Living curtains are usually restricted in size by their supporting structure, installed generally few centimetres from the wall, and as such, no maintenance is required apart from irrigation (optional or compulsory depending on the situation). As a result, the animal biodiversity found on masonry walls, living curtains, green façades and hedges might not be particularly influenced by maintenance. On the other hand, living walls are mostly installed for their aesthetic features and, as such, are subject to high levels of maintenance with frequent interventions. For example, there may be frequent removal of dead leaves/flowers/plants, irrigation water may have fungicides such as potassium bicarbonate (also called baking soda) against mildew, pesticides, acids to rinse the drips, fertilizer (e.g. root development stimulators, foliage stimulators), etc. (information collected from over 15 LW installers/maintainers). Pesticides are sometimes sprayed directly and are usually against nematodes and weevils (herbivorous Coleoptera, usually considered as pests), although maintainers tend to use pesticide and herbicide only when needed. However, the main pesticide used, Met52 (*Metarhizium anisopliae*) has been shown not to affect Hymenoptera (Stolz 1999), but targets beetles (Coleoptera), flies and gnats (Diptera: Brachycera and Nematocera), mites and ticks (Acari), root aphids and whiteflies (Hemiptera: Aphididae and Aleyrodoidae), thrips (Thysanoptera), and overall over 200 species of insects (Bailey & Lelan 2002; Ford 2013; Anonymous 2014). As such, the insect biodiversity on LW may be reduced to the species not susceptible to such biocides and may not be representative of the animal biodiversity that could potentially live on them.

The type of foliage and botanical composition, the position of the growing media and the maintenance interventions make living walls, green façades (including green screens), living curtains, masonry walls, and hedges different habitats for wildlife. Therefore, the different green wall systems need to be considered independently even if they are all using the vertical dimension. For further details on the different green wall systems, please refer to section 2.2.1.

2.5.2 The ecosystem services of green walls

Primarily in Germany and northern countries, significant interest has been generated by green walls and some evidence is now available on their environmental performance, biodiversity value, impact on commercial lettings, etc. (e.g. see Anonymous 1990; Anonymous 2004b). As with other green infrastructure components, green walls have multifunctional benefits and only an integrated approach will unlock their full potential. As such, when studying green walls, a distinction can be made between the initial reason(s) for their installation (e.g. as nest habitat for birds, or for aesthetic improvement and added-value to buildings) and the multiple ecosystem services they will perform in addition. Green façades, living curtains, and living walls are usually studied in urban areas whereas the characteristics of masonry walls (especially stone walls) and hedges are mostly studied in rural areas (see Chiquet *et al.* 2012 and reference therein). Table 2.5 summarises the attributes and functions of green walls in different environments. Whilst the different green wall systems share common functions, their characteristics (such as their size and vegetation composition) may make them more appropriate for different contexts or environments. For example, some will be used primarily as green boundary markers (e.g. urban hedges, green screens) whilst others will be established for advertising or reputational reasons (e.g. living walls). They will be interchangeable in certain situations or functions (e.g. windbreak or rapid change in visual amenity) but not for all purposes (see Chiquet *et al.* 2012 and Table 2.5). From a structural point of view, LWS demand a more complex design (i.e. material involved, control of water and nutrient levels, vegetation diversity) and have higher maintenance requirements than GF (Dunnett & Kingsbury 2008). They also require more energy (for the manufacturing, the installation, to function), which raises the question of their current sustainability unless the technology is improved and the materials are sourced from sustainable or recycled materials (Ottelé 2011). The advantages and disadvantages of the different types of green walls are summarised in Table 2.6.

Despite the research available on their multiple values, their potential is not widely appreciated by the general public (Wolton 2009) which can respond negatively to spontaneous vegetation of urban walls (Millard 2004). Therefore, it is essential to inform the public of their benefits and more generally on the importance of greening the cities. In contrast to being feared for the degradation it may cause to building surfaces, vegetation is now investigated for its ability to conserve and protect the integrity of wall fabric and especially that of historic monuments (Viles *et al.* 2011). Furthermore, green walls can be used to upgrade the overall aesthetic of an area by greening a plaza or improving the appearance of old and/or ugly buildings and structures, as well as creating intimate spaces and reducing vandalism (Crowe 1994; Branas *et al.* 2011; Perini *et al.* 2013). The presence and appearance of a green wall, especially living walls, can contribute to the corporate social responsibility targets of an organisation, improve its image and be used as a form of advertising through the type of planting design (e.g. using logos and abstract representational image, see Fig. 2.7). On the other hand, GF are mainly created for private rather than commercial or industrial use (Dunnett & Kingsbury 2008) due to their ease of establishment and low cost. Living walls can be used for food production (as vertical gardens) in places where horizontal space is costly such as on balconies and/or flats or not easily accessible by the gardener (e.g. wheelchair users). Much of the scientific interest of green walls is coming from the green roofs field (see Köhler 2008; Francis & Lorimer 2011) which has been focusing on the benefits they provide to the urban microclimate, including temperature mitigation, pollutant removal and storm water management (e.g. Oberndorfer *et al.* 2007). As such, previous studies established that green walls mitigate several urban pollutants, especially near busy roads, (i) by improving air quality through filtering and trapping particulates and gasses/aerosols (Ottelé 2011 and references therein), and (ii) by acting as noise barriers through sound absorption, reflection and deflection (see Dunnett & Kingsbury 2008). They significantly mitigate local climate (in terms of temperature, relative humidity, promotion of air circulation), and reduce the heat island effect by impacting the reflection of heat from sealed surfaces and by shading (Ottelé 2011). They improve the thermal insulation of buildings through different mechanisms, and vegetation coverage will protect the façade from climate events (rain, snow, wind flow, freeze-thaw weathering - Sternberg *et al.* 2011). They have also been shown to reduce the storm water runoff (Köhler 2007). All these values are positively correlated with human health and well-being as they create a better living environment (Bringslimark *et al.* 2009). Some of their potential environmental values have not been investigated as for example the mitigation of light pollution, even if the study of thermal insulation through shading gave some information on this subject. As such, the effective shading of green wall was shown to contribute to reduce light pollution within buildings as efficiently as artificial barriers (Pérez *et al.* 2011a).

Despite an extensive range of studies on urban ecology, no previous study in the English literature was found on the value of urban walls covered with vegetation, either naturally or as an artificial man-made structure for animal biodiversity. Green walls have the potential to contribute to the improvement of urban animal biodiversity by creating habitat, food sources (e.g. for wintering birds), corridors, nesting sites, etc. However, the enhancement of animal biodiversity by green walls had not been studied with the exception of German literature (Köhler 2008). In the latter, previous work (see Köhler *et al.* 1993 and reference therein), showed that green façades (either with ivy or grapevines) can be colonized by 19 different taxa of invertebrates such as Araneae, Diptera, Diplopoda, and Siphonaptera. Although important work has been done on the animal biodiversity of green façades in Germany and of green roofs (Grant & Lane 2006; Kadas 2011; Madre *et al.* 2013), the findings are either not accessible to non-German speakers, or not transferable to green walls. Consequently, our understanding of the biodiversity value of green walls for animals was almost non-existent in the international academic area. This PhD project aimed to fill this gap by examining the habitat value of GW for urban animal populations (see chapter 1).

CHAPTER III

GENERIC MATERIAL & METHODS

3. GENERIC MATERIAL & METHODS

This chapter will give generic information relative to the study sites and animal surveys. Specific information on the study of each taxon will be given in the relevant chapters.

3.1 STUDY SITE DESCRIPTIONS

Studying green façades and living walls had different constraints. The first were mostly private, easy to find and to access. However, they had many different characteristics and extensive work had to be made beforehand to decide which characteristics to look at (in terms of a wall's characteristics but also adjacent land) and how to choose a certain homogeneity between sites to avoid too much diversity (e.g. the frequency of trimming). The factors investigated were selected based on literature and feasibility. As such, for example, ambient temperature was not recorded on days of survey and the animal biodiversity was not studied the day before and just after a cut. Living walls on the other hand, were mostly in public areas or corporate organisations in London. Obtaining access was less easy, and due to time and budget constraints, they were selected on their proximity to one another. Due to the relatively new market, established living walls belonged mostly to two main systems (angled plastic modules and rockwool units - see section 2.2.1.1); and particular attention was given to selecting living walls with other systems for the study (although the latter were less abundant).

3.1.1 Green facades in Stoke-on-Trent and Newcastle-under-Lyme

A selection of green facades was made within the cities of Stoke-on-Trent and Newcastle-under-Lyme, North Staffordshire, UK over the summer of 2010 (see map in Appendix 6, hereafter termed 'Stoke-on-Trent', and examples in Fig. 3.1). These varied in size, were boundary or outdoor building walls, and were separated by at least 200 m, typically with many buildings, streets, trees and shrubs between them. A wall was defined as 'green' and suitable for the study if it had a minimum vertical vegetation area of 3 m² with no interruption in said vegetation (i.e. no windows ledges or bare surfaces). Similar walls (in terms of size, aspect, wall material, roof type and adjacent land) but completely devoid of any vegetation were used as controls. Sites were incorporated into the study after authorisation was sought from the owner and it was confirmed that no pesticides were applied on the plants. Each green façade was paired with a single bare wall. Sites were surveyed in random order for each repetition and with each control wall being surveyed immediately before or after its paired green wall.

The green façades used in this study were mostly private walls in residential area and maintained as an aesthetically pleasing feature of the property, trimmed on average twice a year although some were never maintained. For most of them, the owners could not estimate the year of plantation. Despite some owners' intentions at the beginning of the study, some green façades were taken down while the study was on-going for various reasons (the amount of maintenance needed, intolerance of bird noise, change in scenery, etc.), and as such the study sites were removed from the analysis. After removal of such sites, twenty-nine green façades were surveyed in total. However, for snails and birds, only twenty-seven walls were analysed: for two of the walls, the owners informed us at the end of the fieldwork season that they had been removing molluscs, and vegetation was removed on two walls before winter fieldwork which rendered them unusable for bird surveys.

Several characteristics were recorded which fall into three main categories: wall, vegetation and environment. Table 3.1 summarises the characteristics recorded and the percentage of site for each category. The first group included the wall dimensions and type (boundary vs. building), the material, the aspect, and the type of base (i.e. grass, pavement or concrete, with or without humus/dead leaves, bare ground). The characteristics of the vegetation on the wall included: vegetated surface area and height, plant species, type of foliage (evergreen vs. deciduous), and species composition. Only plant species covering more than 10% of the vegetated area were recorded (some walls were covered by many species with some covering less than 5% of the vegetated surface - as such they were not considered in the plant composition). The environment was categorised in terms of the landscape, the immediate locality and land-use (e.g. curtilage or not, residential vs. public), and the immediate area. The vegetation surrounding the study sites (taken within a semi-circle of 20 metre radius around the wall) was also characterised in terms of type and abundance of features: these were all found to fall under the categories of herbaceous trees, herbaceous shrubs, grass and ground-cover plants. The walls were mostly composed of bricks, and the building roofs of tiles. If a green façade had characteristics not shared with other façades, e.g. located in an industrial area when all the others were in residential/public areas, protected by an awning when the others had none, etc. it was not selected for the analysis. Boundary walls were only used if their height was within a range comparable to the building walls (see below).

The climbing plants belonged to the evergreen *Hedera spp.*: *H. helix* common or English ivy, *H. colchica* ‘sulphur heart', *H. colchica* 'dendrata variegata', *H. iberica* atlantic or Irish ivy and *Pyracantha sp.* (trained against the walls); and from the deciduous genera *Wisteria*, *Jasminum* and *Parthenocissus* (*P. quinquefolia* Virginia creeper, and *P. tricuspidata* Japanese creeper or Boston ivy). Of the twenty-nine façades, the mean vertical vegetation area was 21.4 ±2.81 m^2 and ranged from 7.5 to 69.2 m^2, with the vegetation covering the majority of the walls’ area (91.3 ±4.56%). The smallest wall was 2 m high (a boundary wall) and the tallest was 6 m high (a building wall); the mean height of walls was 3.8 ±0.25 m.

3.1.2 Living walls in Birmingham and the London Greater Area

The main suppliers and manufacturers of living wall systems in the UK were contacted at the beginning of 2012 to select potential sites. Twenty-two living walls from six companies (ANS-Scotscape, Bin Fen, Biotecture Ltd., Mobilane®, Grange Construction & Roofing Company Ltd., Treebox Ltd.), were chosen in Birmingham and the Greater London Urban Area (see maps in Appendix 7 and 8 respectively). The systems varied from different plastic modular containers and diverse rockwool units (Fig. 3.2). The plastic modules were either open vertically and slightly angled (n=13, ANS-Scotscape, Fig. 3.2a), or open horizontally like racks of window boxes (n=1, Treebox Ltd., Fig. 3.2b). The Bin-Fen system studied consisted of several plastic pots attached to a steel weld mesh and was aimed at the DIY market (n=2, Fig. 3.2c). The rockwool units were either bare and compacted (n=1, Mobilane®, Fig. 3.2d), covered with geo-textile (n=1, Grange Roofing Ltd, Fig. 3.2e), or with polypropylene (PP) plastic in front (n=4, Biotecture, Fig. 3.2f). Four green screen installations with *Hedera sp.* on a wire meshwork, two in London and two on the Staffordshire University campus were also monitored for comparisons (Fig. 3.2g).

Because of time and budget constraints, the living walls were mainly selected on the basis of their accessibility and their relative proximity to one another. They were outdoor, freestanding or building walls, in private or public areas. All walls were directly accessible either to city-dwellers or to the homeowners (i.e. not separated for example with water features in front). They were installed above sealed surfaces (pavement or asphalt) apart from one wall in Birmingham (Bullring shopping centre) and another in London (King's Fund), directly installed above cultivated ground. They were installed less than 20 centimetres above ground, apart from two walls in Birmingham (Mailbox) and two in London (Finsbury Circus) installed approximately one meter above ground. The wall maintenance was carried out approximately every fortnight by the wall suppliers (although it could be sub-contracted to installers or horticultural companies). The maintenance consisted of (i) a visual survey to check disease or dead plants, (ii) the removal of molluscs, weeds, dead leaves and dead inflorescence, (iii) adjustment of the automatic fertilised water irrigation, (iv) action against pests or diseases if necessary, and (v) occasional trimming. A private wall in London (horizontal plant box system) and the wall in Bullring shopping centre in Birmingham (rockwool with geotextile fascia) were maintained every couple of months only. For these walls, the owners were keeping the manufacturers updated on the state of the wall (in case of water failure, pest or disease).

Characteristics of the wall (type of system, aspect and age), the wall vegetation (surface area, plant composition and density), and the environment (city, landscape, land-use, surrounding vegetation, vehicle and pedestrian traffics) were recorded. Table 3.2 summarises the characteristics recorded and the percentage of site for each category. The environment was categorised into four groups across a gradient from ‘the LW is the only green feature in a 20-meter radius’ to ‘completely surrounded by natural features’ (i.e. green space). Pedestrian and vehicle traffics were categorised into four groups across a gradient from ‘no vehicle or pedestrian area in a 20-meter radius’ to ‘directly along a road or a walking path’.

The evergreen vegetation composition was slightly different on each wall depending on the manufacturers (given in Appendix 5), although some genera such as *Heuchera spp.* or *Asplenium spp.* were found on each studied site. The mean vertical vegetation area was 65.9 ±3.09 m² and ranged from 6 to 200m². The smallest wall was 2.5 m high and the tallest was 12 m high (total height including the bare space underneath); the mean height of walls was 6.7 ±0.72 m with a mean length of 16.5 ±3.09 m.

3.1.3 Establishment of a living wall on Staffordshire University campus

A living wall system from Mobilane® was installed on the Staffordshire University campus in May 2011 (see Fig. 3.2d). North facing, it was surrounded by hard infrastructure components. The green wall was 14 metres wide and 2.4 metres high, covering a surface of 33.6 square metres and erected 0.2 metre from the ground (Fig. 3.3 and 3.4). It was made of 56 modular rockwool panels, each being 1.0 m wide x 0.6 m high. Two different plant treatments were planted on the panels: a flowering group made of *Heuchera* ‘Paris’, *Vinca minor*, *Waldsteinia ternata*, and a non-flowering group made of *Lonicera nitida* ‘Maygrun’, *Polypodium vulgare*, and *Polystichum setiferum* ‘herrenhausen’. At the installation, they were young plants with small leaves and a well-developed root system (Fig. 3.4). The wall was divided in 14 blocks of 4 panels each (see Fig. 3.3). The blocks were planted with one or the other plant treatment alternatively. Within each block, the plants were spread randomly (*i.e.* no stated lines, clusters or specific design). Although cars appear on the Figure 3.4, soon after the installation of the living wall the area was transformed into a pedestrian zone.

3.2 ANIMAL BIODIVERSITY SURVEYS

3.2.1 Protocol

In the subsequent year to the pilot study (see section 1.3), the twenty-nine green façades were surveyed on three occasions per season to examine the seasonal and sampling influences on invertebrate populations. To investigate the effect of seasonality, birds were surveyed in the summer and the winter; invertebrates (i.e. shelled molluscs, spiders and insects) were monitored in the summer and the autumn. In the later, data collection was carried out while deciduous foliage had started to change colour, it finished before leaves had started to fall. Two to six sites were surveyed in a single fieldwork session, depending on the weather and the distance between sites.

On living walls, no preliminary studies were done. As such, the twenty-two established living walls in London and Birmingham were surveyed four times from July to September 2012, i.e. during the peak time of activity for invertebrates (Fasola & Mogavero 1995; Nicholls *et al.* 2001; Hogg & Daane 2010). One fieldwork session was sufficient to survey the nine walls in Birmingham and the two green screens based on the University campus. Two fieldwork sessions (in two continuous days) were needed to survey the thirteen living walls and the two green screens in London.

Invertebrates were surveyed on the new living wall on five occasions, from June to September 2012, with fortnightly intervals.

All surveys were made in daylight. To minimize the effect of weather, no observations were conducted under rainy or windy conditions (Trnka *et al.* 2006; Smith & Wachob 2006; Gollan *et al.* 2010). During each survey, the local weather was recorded (i.e. wind speed, sun exposition and percentage cloud cover). The wind speed was categorised according to Beaufort scale: the range ‘calm’ to ‘gentle breeze’ (i.e. 0 to 3 from an overall scale of 0 to 12) was considered as acceptable fieldwork conditions. Sun exposure of walls was recorded as: fully shaded, in full sun, partially shaded and full cloud cover (no shadows cast).

The surveys took place during the peak time of activity of the different animal groups: invertebrate surveys were carried out during one fieldwork session per day: between 10 am to 3 pm (Dennis *et al.* 2001), and birds inventory were realised during two fieldwork sessions: between sunrise to 5 hours after sunrise (“morning session”), and from 5 hours before sunset to sunset (“evening session”) (Deslauriers & Francis 1991, Trnka & Prokop 2006). Surveys were not undertaken when lighting conditions were not optimal (i.e. lighting was to dull for proper identification). Living walls were not all accessible at the time required for the bird surveys and shelled molluscs were actively removed from living walls by most of the maintenance teams. As such, birds and snails were surveyed only on green facades. However, some snails were captured on living walls and the results are discussed in chapter 5 (see sections 5.5 and 5.6.6-7). Spiders and insects were inventoried both on green facades and on living walls using the same methodology (see sections 3.2, 6.3.2, 7.3.2 for further details). Other invertebrates such as Acari, Collembola, Isopoda, and Myriapoda captured by suction were counted but not identified nor included in the analysis.

Specimens only identifiable at a level above the species were designated with their identified level name (e.g. order, family, subfamily) followed by ‘UI’ for ‘unidentifiable individuals’; they were included in the analysis of the overall abundance but not in the analysis of species richness. Similarly, when too damaged, specimens were discarded for the species richness analysis but included in for the abundance analyse. Specimens identified by morphospecies were referred to as species for the species richness analysis (Nahmani & Rossi 2003; Cardoso *et al.* 2004).

The term ‘plant diversity’ may be used (for GF) to refer to whether the wall was composed of a single plant species (‘monoculture’) or diverse plant species (‘polyculture’); whereas the term ‘plant richness’ (for LW) is referring to the genus richness of plants (see Appendix 5).

3.2.2 Suction sampling of invertebrates

Following the visual survey for snails and spider webs (see sections 5.3.2 and 6.3.2 respectively), a Vortis® suction sampler was used (©Burkard Manufacturing Co. Ltd., Rickmansworth, England - Fig. 3.5). With a collecting area of 0.2 m², the suction device was used at random locations between ground level to two metres above ground. Applied firstly on the foliage surface, the vortis was gradually pushed parallel to the ground as deep in the vegetation as possible with the maximum intensity. At the end of each sample, the collection jar was removed while the vacuum was still running, sealed, and placed into a freezer bag with blocks of ice until sorting (Doxon *et al.* 2011). All suction samples were taken to the lab and stored in alcohol. On green façades and the new living wall on campus, the vortis was applied on five locations; on established living walls, due to their greater size, ten locations were used.

Invertebrate surveys were planned to take place in the spring, the summer and the autumn. However, due to technical problems affecting the equipment, the suction sampling could not be used in the spring, so data are available only for the summer and the autumn.

3.3 STATISTICAL ANALYSIS

Statistical analysis of bird data was carried out using SPSS19.0® and for invertebrate data SPSS 21®. Non-parametric tests were conducted as the data did not meet the assumptions of normality, even after attempts of transformations. As the typical box plots used to represent median data are less easily interpretable, data are presented as means ±1SE.

The non-parametric Kruskall-Wallis tests (KW) and Friedman tests were used for multiple comparisons of independent data and paired data (or repeated measures) respectively. They were followed by post hoc tests with a Benjamini-Hochberg correction (Field 2009) when significant differences were found. Wilcoxon signed-rank tests (WT) were used for the analysis of paired data including seasonality, time of day, and paired comparison between green walls and bare walls, e.g. bird abundance on green walls in summer and bird abundance on green walls in winter. Mann-Whitney U tests (MW) were conducted for the analysis of independent data, i.e. comparisons between the different sampling methods, the type of foliage, the type of wall base, the plant diversity, the aspects, the different LWS, the different web-weaver categories, and the different insect orders, e.g. spider abundance on green walls with deciduous foliage and spider abundance on green walls with evergreen foliage. Linear regressions with stepwise selection procedures (Field 2009) were carried out to analyse the relationships between continuous factors: (i) the abundance and species richness of the different animal groups, and (ii) the vegetation surface area, plant density, plant richness, vehicle or pedestrian traffic volumes, and abundance of surrounding vegetation. On the new living wall, the complexity of habitat structure (two heights and two botanical treatments) was manipulated in a two-factorial design. When directional hypothesis were made, 1-tailed tests were used.

Ordination using multiple correspondence analysis (MCA) was applied to the insect data set to investigate further the complexity of these ecological systems (see sections 7.3.3 and 7.5.6 for further information).

Variables studied and factors investigated for each animal taxon are detailed in the following chapters.

To ease reading, several decisions were made: (i) the sample sizes are not repeated for each statistical result, (ii) for non-significant results the p-value is sometimes given as 'p>0.05' and the z-value is not given in the text, and (iii) the statistical results are given in the text or in tables beneath the related figures as appropriate.

Analyses were carried out on the mean abundance and species richness found on wall on one occasion. The study was not designed to compare the fauna of GF and LW due to difference in period of sampling, as such, only differences in species composition and proportion of individual species and/or families will be discussed when appropriate.

CHAPTER IV

THE VALUE OF GREEN WALLS FOR URBAN BIRD POPULATIONS

4. THE VALUE OF GREEN WALLS FOR URBAN BIRD POPULATIONS

This chapter is based on the article published in Urban Ecosystems (Chiquet *et al.* 2013). It focuses on the value of green façades for bird and investigates the influence of the type of vegetation foliage on bird communities. Bird surveys were not carried out on living walls because of methodology requirements (see section 3.2.1).

4.1 ABSTRACT

This chapter presents preliminary findings of the value of green walls, focusing on green façades, for urban birds. The abundance of birds on 27 green walls and within the area enclosed by a semi-circle of 20 metre radius immediately surrounding them, was compared with 27 paired walls without vegetation (bare walls) and similar surroundings. The study was carried out during the summer and winter of 2010-11 in north Staffordshire (UK). Birds exploited the green walls for various reasons (including nesting, food and shelter) but were never found on bare control walls. The roofs of buildings and the surrounding vegetation were used by birds in both regimes, but birds were more abundant in areas with green walls. The use of green walls by birds depended on the time of day, the season and whether the vegetation was evergreen or deciduous. The birds' activity was always restricted to the upper half of the wall vegetation. Green walls and the immediate surroundings were used by some species of conservation concern in Great Britain (e.g. *Passer domesticus* and *Sturnus vulgaris*). Therefore, encouraging householders and businesses to grow vegetation up walls may be an effective way of providing a range of resources for birds in urban areas without the need for expensive additional land-take.

4.2 INTRODUCTION

In Great Britain and other parts of Europe, urban birds are suffering worrying population declines e.g. *Passer domesticus* house sparrow (De Laet & Summers-Smith 2007) and *Sturnus vulgaris* common starling (Freeman *et al.* 2007). This may be because of a range of factors, of which decreased forage in built-up areas (Murgui & Macias 2010, Vangestel *et al.* 2010) and a lack of nesting opportunities (Evans *et al.* 2009, Summers-Smith 2009) have been identified as potentially important.

This study is a first attempt to report the value to birds in the urban environment of climbing plants or wall shrubs growing on external walls (i.e. green façades). The main focus was on (i) the seasonal impacts and (ii) the effects of foliage (i.e. deciduous and evergreen) on bird abundance and species richness. As such, the study was designed to test the following hypotheses about the value of green façade as a bird habitat:

1. Green façades with substantial amounts of vegetation would have more birds and be more species rich than bare walls.
2. Green façades with evergreen foliage are expected to show higher abundance and species richness than green façades with deciduous foliage. Vegetation surface area is expected to be positively related with bird abundance and species richness.
3. Bird abundance and species richness will be affected by the time of day and the season of sampling.
4. Green façades will affect the immediate surroundings in such way that birds will be more abundant and rich around green walls that around bare walls.

4.3 MATERIAL AND METHODS

4.3.1 Study sites

For detailed information on green façades study sites, please refer to section 3.1.1.

4.3.2 Bird inventory on green façades at dawn and dusk

For detailed information on bird surveys, please refer to section 3.2.1.

Observations were made 15 metres from the wall, using binoculars, by the same surveyor wearing neutral colours to minimise bird disturbance (Campbell 2011). Data were collected after a 7-minute acclimatisation period in order to give the birds time to get used to the observer's presence and each survey lasted 20 minutes per wall (Fernandez-Juricic 2000). To compare the effect of time of day on observations, walls were surveyed between sunrise to 5 hours after sunrise ("morning session"), and from 5 hours before sunset to sunset ("evening session") (Deslauriers & Francis 1991, Trnka & Prokop 2006). Surveys were not undertaken when lighting conditions were not optimal (i.e. lighting was to dull for proper identification).

Species were identified using Svensson *et al.* (2009) and each individual's position was recorded, either (i) on the wall, (ii) on the roof (corresponding to the roof of the buildings or to the top of the wall creating an angle of at least 45° with the vertical surface for the boundary walls) or (iii) on the visible vegetation surrounding the wall within a semi-circle of 20 metre radius.

4.3.3 Data analysis

The variables studied were bird abundance, species richness and individual species abundance.

The factors investigated were: the impact of vegetation on walls (n=27) compared to the paired control (i.e. bare walls, n=27), the location where each bird was found (i.e. positions on the wall, roof, surrounding vegetation), seasonality effect (summer vs. winter), the effect of time of day (4 hours before dawn “am”, or after dusk “pm”), the type of foliage (evergreen vs. deciduous), and the vegetation surface area. For detail of the statistical tests, please see section 3.3.

4.4 RESULTS – VALUE OF GREEN FAÇADES FOR BIRDS

4.4.1 Bird abundance and richness on green walls compared to bare walls

Overall, 83 birds from nine species and six families (Table 4.1) were observed in association with walls (i.e. on the wall surface, roof and surrounding vegetation). Some species were only seen on the roof of buildings (e.g. *Corvus monedula* Eurasian Jackdaw, *Corvus frugilegus* rook or *Pica pica* Black-billed Magpie), whereas the others were associated with the wall and the roof, and/or the surrounding vegetation (Table 4.1). Too few individuals of each species were observed to allow for separate analyses.

When flocks of birds (principally *S. vulgaris* but also *P. domesticus*) entered the study area, their presence and position were recorded but they were excluded from analysis because their dynamic nature prevented accurate counting. Nevertheless, more than double the number of flocks were found on green wall sites compared to bare wall sites (23 and 10 respectively).

Significantly more birds were found in association with green walls than bare walls, either considering the whole study area or considering only the surface of the walls (Table 4.2). In bare wall sites, birds were only found on the roof; whereas in green walls sites, birds were found in all areas (roof, wall surface and surrounding vegetation) with most on the wall itself. In pair-wise comparisons, there was no significant difference in the use of green or bare wall roofs by birds. Birds were found on the surrounding vegetation associated with green walls but never with control walls, although the difference was not significant (Table 4.2).

4.4.2 Effect of time of day

The impact of time of day on observation was analysed by comparing the bird abundance on 21 green walls and 21 bare walls that were surveyed during both the ‘morning session’ and the ‘evening session’. More birds were found on green walls compared to bare walls whatever the time of survey ($H_{(3)}$= 27.85, p<0.001 - Fig. 4.1). Birds were significantly more abundant in and around green walls in the morning than in the evening sessions (z=-2.50, p=0.012), whereas there was no significant difference between ‘morning’ and ‘evening’ surveys for birds associated with bare walls (z=-0.816, p=0.414). More birds were found interacting with green walls than bare walls during the early morning surveys (z=-2.59, p=0.009), whereas evening surveys showed no difference (z=-0.810, p=0.412).

As significantly fewer birds were recorded in the surveys prior to sunset compared to the 'morning session', the following analyses concentrate on morning data only.

4.4.3 Seasonality and foliage influences

Seasonal differences were analysed by comparing the bird abundance of 25 green walls and 25 bare walls surveyed in both summer and winter. Whatever the season of survey, more birds were observed interacting with green walls compared to bare walls (Fig. 4.2a, Table 4.3). There was no significant effect of seasonality on bird abundance on bare walls; whereas significantly more birds were found in association with green walls in the winter compared to the summer. Moreover, there was a significant difference between bare walls and green walls in the winter and in the summer (Fig. 4.2a, Table 4.3).

Whatever the season of survey or the type of foliage (evergreen or deciduous) more birds were observed interacting with green walls compared to bare walls (Fig. 4.2b, Table 4.3). During the summer, there was no significant difference in the number of birds found in green walls with evergreen foliage, deciduous foliage and in bare walls. A significant difference was evident in the winter, with more birds associated with evergreen plants than deciduous plants and bare walls. Birds were significantly more abundant in evergreen foliage in winter than summer; whilst seasonality had no effect on the bird abundance in deciduous foliage (Fig. 4.2b, Table 4.3).

4.4.4 Effect of the wall size on bird abundance and species richness

Bird population abundance and species richness were not significantly affected by the size of the different green walls (p=0.125, p=0.187 respectively). Conversely, all the birds observed on the surface of green walls were found on the upper half of the walls, irrespective of their height (from 2 to 6 m). Similarly, in the surrounding vegetation, birds were observed in the trees or the shrubs but never on the ground.

4.5 DISCUSSION

4.5.1 Value of green façades

Birds clearly exploited the vegetation covering walls, whereas no birds were found on bare walls. Furthermore, the avian abundance was far greater around green walls than around bare walls (i.e. on the roof and in the surrounding vegetation). This association may depend on the resources available (Hinsley & Bellamy 2000) and suggest that GF may be providing additional resources to the surrounding vegetation: some species may nest within the wall vegetation, whereas some may use it only as a refuge, or others for food (e.g. invertebrates, berries).

Thus, Johnston & Newton (1993) noted that birds such as *Troglodytes troglodytes* wren, *Turdus merula* blackbird, *Turdus philomelos* song thrush and *P. domesticus* may use climbers as a nesting habitat. In this study, birds were only recorded visually, no aural records were made. As such, it is likely that our records of birds on the green walls are an underestimate, as stationary birds under cover would not have been recorded.

4.5.2 Effect of time of day

Morning and evening surveys are usually combined for bird monitoring as morning sampling alone does not give an accurate estimate of relative abundance (Trnka *et al.* 2006). However, in this study, more birds were observed on green walls during mornings compared to evenings. This may be related to diet, with insectivores being most active in the morning when their prey is least active due to lower ambient temperatures (Deslauriers & Francis 1991, Trnka *et al.* 2006). However, in this urban study, another explanation may be the greater anthropogenic disturbance during evenings than during mornings. The study sites were in residential areas, and more human activity was observed at the end of the day (with children playing in gardens or workers returning home) whereas during morning surveys no, or very few, people were seen by the surveyor (unquantified obs.). Thus the suitability of an urban habitat for bird selection appears to be more influenced by human disturbance than any other environmental factor (Fernandez-Juricic 2000).

4.5.3 Seasonality and foliage influence on birds abundance and their use of the wall

In this study, green walls appear to be of most value to birds in the winter, and it is clearly the evergreen species which are the most attractive; presumably as they provide shelter and refuge (e.g. acting as source of heat, providing a perch-post protected from the wind) when deciduous green walls have lost their leaves. Arnold (1983) showed that, in winter, hedgerows provide physical shelter and are an important source of food for birds. Many studies (see Hinsley & Bellamy 2000) indicate that the relationships between bird occurrence and hedgerow characteristics differ between summer and winter, with food supplies being more important in winter (Arnold 1983, Moles & Breen 1995). Evergreen species such as ivy can provide a supply of fruit to birds in the cold season as the berries ripen from December to January, with the main bird feeding period on berries starting in January (Jacobs *et al.* 2010). In addition, green walls may make suitable nesting habitat for a range of species provided that they are mature and of sufficient volume to provide suitable cover, but this aspect was not systematically investigated in this study.

Discussions with owners of houses that hosted the study of green façades elicited records of roosting and nesting by species such as *S. vulgaris*, though no published work was found to support nesting by this 'cavity-nesting' species in vegetation (Fernandez-Juricic 2000). Casual observations indicated that *P. domesticus* and *T. merula* did use some of the study walls as nesting habitat, as found by Clements *et al.* (2006), Anderson (2006) and Kurucz *et al.* (2010).

4.5.4 Effect of the vegetation surface area on bird biodiversity

Birds were only found on the upper half of the wall vegetation irrespective of the size of the wall. Tree and shrub structure have been shown to affect bird responses (Franzreb 1983, Duncan & Bednekoff 2006, Campos *et al.* 2009) and some species (e.g. *Erithacus rubecula* European robin) appear to be more affected by shrub height than others (e.g. *S. vulgaris*, *P. domesticus* - see Campbell 2011). The height of perches used by birds for singing may depend on the density of the surrounding habitat (Scherrer 1972) and the preference of most birds for shelter in the upper levels of vegetation may be because taller structures offer a larger area of refuge (Campbell 2011) and a better vantage point (Moller *et al.* 2005), potentially reducing the risk of predation (Campos *et al.* 2009).

This study, whilst of limited extent and duration, has demonstrated that vertical building surfaces colonised by climbing vegetation are used by birds in the urban environment. Without requiring additional land take or sophisticated and expensive modification to buildings, such structures may be important for promoting the conservation of species declining in abundance (by 62% in the last 25 years for *P. domesticus* and by 66% in the last 35 years for *S. vulgaris* - they are both red listed as species of high conservation concern in Great Britain (Eaton *et al.* 2009)). The trend to higher building densities in urban areas is likely to result in lower urban bird densities (Evans *et al.* 2009); green walls may be one method of mitigating the negative impacts of such developments on forage, cover and nesting opportunities.

4.6 AKNOWLEDGMENTS

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CHAPTER V

THE VALUE OF GREEN WALLS FOR URBAN SNAIL POPULATIONS

5. THE VALUE OF GREEN WALLS FOR URBAN SNAIL POPULATIONS

This chapter is mainly based on a manuscript submitted to Urban Forestry & Urban Greening (Chiquet *et al.* under review 1). It focuses on the value of green façades for snail communities and investigates the influences of sampling method on population estimates. Initially because snails and other molluscs were actively removed from living walls by the maintenance teams, no study was planned to examine the value of living walls for snail (for definition of green façades (GF) and living walls (LW) see section 2.2.1). However, during studies of other invertebrates on living walls, the suction sampler caught a few snail specimens and these data are covered in this chapter.

5.1 ABSTRACT

Focusing primarily on green façades, i.e. GF, walls covered with climbers and wall shrubs, the study investigated their value to snails. In an urban area in north Staffordshire, UK, snail samples were collected from 27 green walls and 27 equivalent bare walls in the summer and autumn of 2011. Total snail abundance, species richness, and the individual species abundances were analysed to evaluate the value of urban green walls as a daytime habitat for shelled gastropods. Two active sampling methods were used: visual searching and vortis suction sampling, to ensure a comprehensive audit of snail species composition and to compare the efficacy of the different survey methods. Snail populations were significantly more abundant and diverse on green façades (489 snails, 7 species) than on bare walls (6 snails, 2 species). Although the two sampling methods showed similar abundances of snails on green walls (4.2 ±0.93 and 3.6 ±0.56 snails per wall for visual searching and suction sampling respectively), they sampled different species mainly related to the size of the shell (shell diameters above 15 mm for visual searching and below 15 mm for suction sampling). The study showed suction sampling gives a more comprehensive estimate of snail species composition of green walls than visual searching, whilst the combined use of the two sampling methods gives a better estimate of the individual species abundance. The time of year of sampling and the type of foliage affected the snail abundance, species richness and age groups but not the species composition.

The unplanned capture by suction sampling of 60 snails on the six different types of living walls systems (n=23, based in Birmingham, London and Stoke-on-Trent, UK) showed their comparable attractiveness for snail populations. Despite active hand-removal on living walls by the maintenance teams, living walls appear to be used relatively more by snail species (9 species, 6 families) than green façades (7 species, 4 families). This may be related to greater plant diversity, more diverse vegetation structure and particularly the presence of

growing media on LW, providing damper conditions more suitable for molluscs than the dryer surface of GF.

Molluscs are of value as they act as essential detritivores and food sources for small mammals and birds. The study demonstrates that vegetating walls provides additional habitat for terrestrial molluscs in urban areas.

5.2 INTRODUCTION

Establishing potential habitat or refuge in urban areas for snails, which have limited dispersal abilities (Hausdorf 2007), is important as they provide many ecosystem services (Clergeau *et al.* 2011); the most evident ones being as consumers of both living and decaying vegetation (Wright & Aungst 2001) and food sources throughout the year for small mammals and birds (e.g. shrew (Rychlik 2002), thrushes (Cameron 1969)). As poikilotherms, snails' activity is restricted in Northern Europe to the warmer months of the year, from early summer to late autumn (Iglesias *et al.* 1996). In England, activity times were established between April to September in Northumberland (North-East England (Perry & Arthur 1991)), and between May to October in Hertfordshire (South-East England (Cameron 1969)). Following these findings on helicid land snails (*Cepaea spp*. and *Cornu aspersum* (Müller, 1774)), this study will include an analysis of seasonality on snail species richness and abundance in Staffordshire (Midlands, England).

With numerous invertebrate sampling techniques available (Clergeau *et al.* 2011), deciding which technique to use is difficult in a context where no previous studies have been carried out, as in this case on vegetated/unvegetated vertical surfaces. Each technique is likely to have inbuilt biases on the nature of the samples collected and on the ability of the method to meet research objectives (Doxon *et al.* 2011). Therefore, snail populations were compared when collected using (i) an invertebrate vacuum suction sampler ('vortis') and (ii) a visual search (hand-picking snails).

Factors that are known to affect the distribution of snails which may be relevant on green walls include: the type of foliage (affecting level of palatability (Cornelissen 1999)), increased plant diversity resulting in greater structural heterogeneity (Labaune & Magnin 2002), the vegetation surface area and the base of the wall (Szybiak & Błoszyk 2009). Although the surroundings might affect snail communities, they were not taken into consideration in the study.

The aims of the study were: (i) to evaluate the value of urban green façades for snails during the summer and the autumn, and (ii) to appraise sampling methods for studies of snails on green walls. As such, the study on GF was designed to test the following hypotheses about their value as a snail habitat:

1. Snail total abundance and species richness will be greater on green façades than bare walls.
2. Seasonality will affect snail abundance, species richness and species composition on GF, especially depending on the type of foliage (deciduous vs. evergreen).
3. Vegetation surface area and plant diversity will be related to snail abundance and species richness.
4. The type of base of the wall (e.g. bare ground, concrete with or without humus) will affect snail abundance and species richness on the green façade.
5. Different sampling methods will have inbuilt biases such that abundance, species composition, individual species abundance, and age structure will vary with the approach. As such, snail abundance will be higher using suction sampling than *in situ* searching.

Maintenance teams removed molluscs on living walls (every fortnight on average); as such, it was not planned to study the value of living walls for snail populations as opposed to green façades (i.e. no visual searching was carried out). Nevertheless, some specimens were caught by the vortis suction and the data are explained and discussed below.

5.3 MATERIAL AND METHODS

5.3.1 Study Sites

For detailed information on study sites, please refer to section 3.1.1 for the green façades, to section 3.1.2 for the established living walls, and to section 3.1.3 for the new living wall.

5.3.2 Snail surveys

For detailed information on snail surveys, please refer to section 3.2.

On green façades, during each survey, ten non–overlapping areas of 0.2m^2 were randomly selected on each wall, between ground level and two metres above ground. Five were visually searched for molluscs on each stem and leaf; the search time depended on the density of vegetation. The surface of the vegetation (or wall surface in the case of controls) was searched first, followed by searching within the vegetation (between the surface of the vegetation and the wall) and then the wall's surface (if accessible). Each snail found was identified, marked with a unique number on the shell surface using a permanent marker pen (Impega®) and released back into the vegetation at its original capture point. If unidentifiable in the field (e.g. species difficult to identify without a microscope because of the shell size or developmental stage), the specimen was not released back into the vegetation but taken to the lab and stored in alcohol. An 'invertebrate suction sampler was used on the five other locations (see section 3.2.2 for further details on methodology).

On living walls, the suction sampling was used primarily for the capture of insect and spider specimens (see chapters 6 and 7) but also captured a few snail specimens.

In the lab, snails were identified by Dr. Dave Skingsley from Staffordshire University, using Kerney & Cameron (1979) and Pfleger (2000). A distinction was made between juvenile/subadult and adult forms by, respectively, the absence or presence of a reflected shell lip (Perry & Arthur 1991). Some specimens were only identifiable to genus level and were not include in the analysis of species richness, unless no species were identified in the genus (e.g. *Helix sp.*). Specimens only identifiable to family level were given the family name followed by 'UI' for 'unidentifiable individuals'; they were included in the abundance analysis but discarded from the species richness analysis unless no other specimens were found in the family (e.g. Succinidae UI). When empty or too damaged, shells were discarded and not included in the analysis. Some specimens of **the** species *Cepaea nemoralis nem.* and *Cepaea hortensis* could not be separated out to species level as the alcohol, used for preservation of the samples, faded the colour of the lip (the usual way of distinguishing the two species (Kerney & Cameron 1979)).

5.3.3 Data Analysis

Because the adult form of some of the species found in this study (e.g. *Merdigera obscura*) are smaller than the juvenile form of others (e.g. *Cornu aspersum*), analysis was carried out on snail abundance by splitting it into two categories ('large shells': above 15 mm maximum shell dimension vs. 'small shells': under 15 mm maximum shell dimension, see Schamp *et al.* (2010)). The length along the longest axis was used as a measure of maximum shell size, according to Lozek (1956) and Kerney *et al.* (1983) (in Schamp *et al.* 2010).

The variables studied were: snail abundance, species richness, abundance of individual species, shell size and age structure. The factors investigated were the impact of: vegetation on walls (n=27) compared to the paired control (i.e. bare walls, n=27), seasonality (summer vs. autumn), sampling method, the type of foliage (evergreen (n=21) vs. deciduous (n=6)), the vegetation diversity (whether the green façade consisted of a single plant species (n=17) or many species (n=10)), the vegetation surface area, and the base of the wall. For detailed information on the GF characteristics, please refer to Table 3.1.

Comparative analysis of the two sampling method were carried out. However, as the areas of sampling using suction and visual searching were not overlapping, aggregation of the results was possible. For detail of the statistical tests, please refer to section 3.3.

5.4 RESULTS – VALUE OF GREEN FAÇADES FOR SNAILS

5.4.1 Snail populations in green façades compared to bare walls

On GF, 209 snails were found using visual searching and 280 snails captured via suction sampling. No snails found using visual searching were recaptured on a following survey. The 489 captured snails belonged to seven species from four families, with a small group of unidentifiable individuals (6.7%, see Table 5.2 in section 5.6.7). Three large aggregations of snails were found and excluded as atypical; when included in the analysis, these data did not change the trends of the results but could alter the significance of the tests due to the high variability amongst the subject groups. Thus, a mix of 183 juveniles belonging to the genera *Cornu* and *Cepaea* were removed from two suction samples and 96 adults *C. aspersum* were removed from a single visual searching survey.

On bare walls, six snails belonging to the genus *Cornu sp.* and *Lauria sp.* were found by visual searching and none using suction sampling. Significantly more snails were found on green façades than bare walls ($H_{(3)}$= 56.31, p<0.001 - Fig. 5.1), whatever the sampling methods (visual searching: z=-3.69, n=27, p<0.001; suction: z=-4.21, n=27, p<0.001). The species richness could not be compared due to the small richness on bare walls. Subsequent analyses focused only on factors affecting snail abundance and species richness on green walls.

5.4.2 Efficiency of sampling approach and seasonality influence on snail populations

In total, the two sampling methods showed similar snail abundances on green façades (p=0.731 - Fig. 5.1). However, when methods and seasonality were compared, differences were evident ($H_{(3)}$= 9.11, p=0.027 - Fig. 5.2). Snails were significantly more abundant in the autumn than the summer using visual searching (z=-3.32, n=27, p=0.001), the trend being opposite but not significantly different using suction sampling (p=0.241). In summer, significantly more snails were captured by suction than observed by visual searching (z=-2.33, n=27, p=0.020). In autumn, approximately twice the number of snails were observed *in situ* than captured by suction, although the difference did not achieve significance (p=0.108).

Species richness was similar whatever the method used and the season of sampling ($H_{(3)}$= 5.78, p=0.123 - Fig. 5.3).

Seasonality and survey method significantly affected the age of snails found (see Fig. 5.4 and Table 5.1 for statistical results). When samples from both seasons were aggregated, there were more adults found than juveniles by visual searching (z=-3.44, n=27, p=0.001) and by suction sampling (z=-1.96, n=27, p=0.050). This was also the case for each individual season (although not always significantly, see Table 5.1).

During visual searches, both age groups were more abundant in the autumn than the summer (although not significantly for juveniles after the Benjamini-Hochberg correction, see Table 5.1). During suction surveys, seasonality did not show an impact on either adult or juvenile.

When samples from both seasons were aggregated, significantly more juvenile snails were captured by suction then observed *in situ* (z=-2.30, n=27, p=0.021). This was also the case during the summer (Fig. 5.4, Table 5.1). No clear effect of sampling method appears on the adult group as more were captured by suction in the summer and more were observed *in situ* in the autumn (Fig. 5.4, Table 5.1).

5.4.3 Shell size and individual species abundance

Sampling methods caught different snail categories ($H_{(3)}$= 18.42, p<0.001 - Fig. 5.5), significantly more small shells were found than large shells (z=-3.74, n=27, p<0.001) using the suction method, whilst by sight, more large shells were found than small shells (z=-2.02, n=27, p=0.047).

No species were found using visual searching that were not found using suction (Fig. 5.6). Among the seven species found on green façades, *M. obscura*, *T. hispidus*, *L. cylindracea* were only found in suction samples. *C. aspersum* and *C. hortensis* were significantly less abundant in the suction samples than observed *in situ* (z=-3.39, p=0.001 and z=-2.0, p=0.046 respectively), whereas other species were more abundant in the suction samples: *T. hispidus* (z=-2.21, p=0.027), *T. striolatus* (z=-2.85, p=0.004) and *L. cylindracea* (z=-2.03, p=0.042). The unidentifiable specimens were as abundant in the visual searching samples as in the suction samples (p=0.228).

5.4.4 Effect of foliage type on capture rates and on seasonality

When samples from both sampling methods were aggregated, snails were more abundant in evergreen foliage (9.0 ±1.11) than in deciduous foliage (3.5 ±1.31) in total (z=2.22, n_1=21, n_2=6, p=0.022), in the summer (z=-2.33, n_1=21, n_2=6, p=0.020 - Fig. 5.7a) and in the autumn (z=-2.12, n_1=21, n_2=6, p=0.034 - Fig. 5.7a). Similarly, snails were more species-rich in evergreen foliage (4.4 ±0.35) than in deciduous foliage (2.0 ±0.67) in total (z=-2.53, n_1=21, n_2=6, p=0.010) and in the summer (z=-2.45, n_1=21, n_2=6, p=0.018 - Fig. 5.7b), but not in the autumn (p=0.195). However, when sampling methods were examined separately, snail abundance and species richness were similar on both types of foliage, in total and in each season (p>0.05).

5.4.5 Effect of plant diversity, vegetation surface area, and the base of the wall on snail abundance and richness

Plant diversity, i.e. whether green façades consisted of a single plant species (monoculture) or many species (pluriculture), did not influence snail abundance and richness whether data from both sampling methods were aggregated (p=0.638; p=0.596 respectively) or examined separately (visual searching: p=0.294, p=0.295; suction: p=0.636, p=0.864 respectively).

No relationship was found between vegetation surface area and snail abundance or species richness whether data from both sampling methods were aggregated (p=0.265; p=0.337 respectively) or examined separately (visual searching: p=0.291, p=0.727; suction: p=0.616, p=0.074 respectively).

The base of the wall was categorised into grass and/or dead leaves (9 walls), pavement or concrete with or without humus (8 and 5 walls respectively), and bare ground (5 walls) (see Table 3.1). For each sampling method, statistical analysis showed no influence of the base type on snail abundance or species richness on the green façades (visual searching: p=0.601, p=0.140; suction: p=0.903, p=0.936 respectively), nor when the samples from the two sampling methods were aggregated (p=0.601; p=0.929 respectively).

5.5 RESULTS – VALUE OF LIVING WALLS FOR SNAILS

On living walls, both established (Birmingham and London) and newly installed (University of Staffordshire campus), 60 snails were captured by suction sampling. Snails were caught on 14 walls out of 23 and none were captured on the four green screens. Nine species and six families were identified with a small group of unidentifiable individuals (Table 5.2).

Snails were present on all types of LW, the captured snails were small (either from ‘small shelled’ species or juveniles of ‘large shelled’ species). The species richness by wall was 1.1 ±0.29 and up to seven specimens and five species could be found on a LW in a single survey. As most of the maintenance teams were actively removing molluscs on the LW, no statistical tests could be run on the data.

5.6 DISCUSSION

The obvious result of this study is, as expected, that snails clearly exploit the vegetation covering walls during the day and rarely use walls without vegetation. Previous work (Chiquet *et al.* 2013) has shown that birds use vegetated walls more than unvegetated walls and this may be partly related to the availability of food resources of which molluscs form one component (Eeva *et al.* 2010). The association between green façades and snails may depend on different conditions: availability of food resources, security provided by vegetation, piles of leaf litter for hibernation, protection against desiccation, etc. Green walls may be used as an exclusive habitat or as a component of a corridor (along with grass, flowerbeds, etc.) between different green spaces in urban areas. Continuous corridors are essential for active land snail dispersal (Baur & Baur 1993a), and, as such, a network of green walls along with other green infrastructure components, may therefore have the potential to facilitate snail dispersal in urban areas. No snails were captured twice on a GF, this could be a result of dispersal across other sites, important dispersal on the walls themselves or due to predation.

The small number of snails found on the bare walls during daytime in this study is probably a result of the lack of protective cover. Nevertheless, it is possible that on bare walls (as on green walls) some very small species or individuals may have been able to use small spaces such as cracks in mortar. Therefore, they may have been protected from capture, even by the suction sampling device, and remained undetected.

As the surveys occurred in daytime, it is likely that snails were sampled primarily during their resting period and may not reflect their nocturnal distribution when snails would be expected to be more active and dispersed (Cameron & Carter 1979).

5.6.1 Species composition on green façades

Irrespective of the size of the vegetated wall, up to five different species were found simultaneously on green façades, whatever the season or the sampling method. The same species composition was found during the summer and the autumn. *C. hortensis* is a species generally located in woodland edge habitats, on walls, and in disturbed places (Anderson 2010). Kerney (1999) suggests that, in Britain, it prefers shadier and more moist places than *C. nemoralis nem.*, which lives in shaded, rocky or humanly disturbed habitats such as gardens. *C. aspersum* is a ubiquitous species in dry or base-rich grassland, stone walls or hedgerows, strongly tied to humanly disturbed places (Anderson 2010). *L. cylindracea* is a ubiquitous species on walls, rocks and screes, in woodlands and gardens (Anderson 2010). Another species typical of synanthropic habitats (e.g. garden) is *T. striolatus*. It is, as *C. hortensis*, found in woodland, waste ground and around old buildings and gardens (Anderson 2010). Conversely to these five species, *T. hispidus* is mostly found in wet, shaded habitats and, is not attracted to gardens (Anderson 2010). Similarly, *M. obscura* prefer warm, south-facing places, and lives principally on minimally disturbed calcareous rocks and walls, often in light woodland or scrub (Anderson 2010). It is a Priority species in Northern Ireland and listed as Endangered (EN) in the republic of Ireland (Byrne *et al.* 2009). These snail species were usually based in different habitats, and their presence on green façades show the attractiveness of this urban environment structure for different habitat groups.

5.6.2 Effect of season on capture rates

Both the seasonality and sampling methods affected the abundance of snails found on green façades. Using the suction method, more snails in terms of abundance and species richness (mostly small snails) were found in the summer, whereas visual searching revealed higher snail abundance and species richness (mostly large snails) in the autumn. As such, snail abundance and richness were affected by the seasonality as expected, but the effect was dependent on the sampling method used and not the type of foliage. Furthermore, the hypothesis that suction sampling would be more efficient than visual searching for surveying snail populations on green walls was not confirmed, as it was only in catching small-bodied snail that suction sampling was more efficient than visual searching (although this could depends on the skills of the observer, see also section 8.2 and below).

More snails were found in evergreen foliage than in deciduous foliage overall, when samples from both sampling methods were aggregated, but not within seasons due to the overall low snail abundance. Due to the relatively few study sites with deciduous foliage, it is possible that the validity of the findings could be questioned despite the significance of the results. As such, although evergreen foliage (mainly composed of *Hedera spp*.) might provide higher protection and shelter (see Shikov 1984), snails might have been equally attracted to deciduous foliage for the higher palatability of the leaves (Cornelissen 1999). The absence of any effect of foliage on snail populations in the autumn may be related to the fact that whilst deciduous foliage had started to change colour, the data collection took place before the leaves started to fall.

5.6.3 Snail age structure on green façades

Whatever the season or method used, more adults were found than juveniles on green walls. Snail egg deposition occurs from the end of May to the beginning of August (Baur & Baur 1993b) so the timing of the surveys may be related to the lower number of juveniles found in the summer compared to adults. Moreover, whilst juveniles of the largest species in the central European assemblages can usually be identified and recorded (Hausdorf 2007), it can be difficult to sample juveniles of small species in vegetation. This may explain the lower number of snails found by visual searching, especially in the summer.

5.6.4 Comparison of the sampling methods on green façades

The estimations of snail abundance and species richness were similar using visual searching and suction sampling. However, the vortis device captured mostly small snails (shell size below 1.5 cm), whereas the visual searching method revealed larger snails (above 1.5cm). The suction power of the vortis might be the explanation for its ability to capture small snails that would probably be easier to dislodge than large snails. Furthermore, visual searching is highly dependent on the ability and the experience of the observer and is more time-consuming. Being aware of these methodological limits is important when analysing results (especially the risk of missing small individuals - Clergeau *et al.* 2011).

Three species were only found using suction, whereas all species observed *in situ* were captured by suction. Thus, the use of suction sampling alone would have given a comprehensive estimate of the species composition of snails, whereas the combined results of methods, sampling different strata and invertebrate groups, are likely to give a better estimate of the relative species abundance among walls. This finding, along with the different age structure by sampling method, highlights the importance of using, whenever possible, more than one sampling method when studying snail populations on green walls.

5.6.5 Effect of the characteristics of the green façades on snail abundance and richness

Previous studies have not identified correlation of ground vegetation cover (either woody or herbaceous) with land snails (Kiss *et al.* 2004; Carmel & Stoller-Cavari 2006). The results of this study suggest that this is also the case for wall vegetation. No relationship was found between the snail abundance and richness, and whether the vegetation on GF was composed of a monoculture or of polyculture. Also found by Dvořáková *et al.* (2014), this absence of relationship may be related to the lack of heterogeneity of the study sites, which are mostly composed of *Hedera sp.* (Labaune & Magnin 2002).

Snails on green façades were not influenced by the type of base of the wall. This may be surprising as snail abundance has been previously shown to be related to the composition (e.g. amount of woody debris) and the depth of the leaf litter (Kappes *et al.* 2009; Clergeau *et al.* 2011). This may be because snails find the microclimate, the protection and extent of the resources they need within the green walls superior to that at the base, at least in the summer and the autumn. However, it is possible that the presence of litter influences snail communities in winter as it has been shown in hedges (Szybiak & Błoszyk 2009). More experimental research is required to investigate these aspects further.

5.6.6 Snail populations on living walls

Despite the active hand-removal of snails on living walls for pest control reasons, several snails were caught by suction. Their presence on each system, even on living walls installed a few decimetres above ground like the rockwool unit system on the University Campus, the plant pot system in London or the angled plastic module system in Birmingham shows a similar attraction of living walls as habitat. The captured specimens were small, either from ‘small shelled' species or juvenile of 'large shelled' species, certainly due to the active hand-removal. Due to the context of the study, these results can only be seen as provisional and more work is required on living walls where snails are not actively removed.

Their complete absence on green screens in London and on the University campus may be related to the reduced foliage density on the meshwork and the relative lack of protection for snails on this system. Some snails may have been present at the bottom of the green screens in the accumulated litter (Kappes *et al.* 2009; Clergeau *et al.* 2011) that were not included in the area of sampling of the suction device.

As for GF, the snail species found on living walls come from varying habitats. *C. cf. lubrica*, usually found in moss, is a common species in lime mortar constructed walls; it is also often found in hedgerows and woods as is *D. rotundatus*. *C. edentula*, *T. hispidus*, and *V. antivertigo* (Draparnaud, 1801) are mostly found in wet, shaded habitats (see section 5.6.1), whereas *C. cf. lubricella* is more restricted to dry, warm habitats. *V. antivertigo* is a Priority species in Northern Ireland and listed as Vulnerable (VU) in a recent red list for the Republic of Ireland (Byrne *et al.* 2009).

5.6.7 Comparison of snail populations on green façades and living walls

Irrespective of the size of the vegetated wall, up to five different species could be found simultaneously on GF and LW. The snail species composition varied considerably between GF and LW (Table 5.2); snails were found on 12 GF out of 27 and on 14 LW out of 23 (Birmingham, London and the University campus LW) using suction sampling. Although no comments can be made on the total or relative species abundances, and despite the hand-removal, living walls appear to be used relatively more by snail species (9 species, 6 families) than green façades (7 species, 4 families). This could be due to the higher diversity of plant composition on LW compared to GF (Gosteli 1996; Sætersdal 2004) which provide a better structural heterogeneity (Labaune & Magnin 2002). In addition, the presence of rooting media on living walls, instead of only at the base as for GF, makes it easier for snails to find shelter and humidity even if the hand-removal of dry leaves by the maintenance team may be detrimental to snails (Norris pers. comm.). The relative high abundance of the family Succinidae and the species *V. antivertigo*, which are typical of constantly wet sites (Norris pers. comm., Cameron & Redfern 1976) and are only present on living walls and not green facades, tend to support this hypothesis. The 'tree or woodland species', *C. edentula* and *M. obscura* were found on both living walls and green façades; as were the 'grassland species' (*C. hortensis*, *C. nemoralis nem.*, *C. lubrica*, *C. lubricella*, *C. aspersum*, and *Helix sp.* - Cameron & Redfern 1976) and the 'roadside' species (*T. hispidus* and *T. striolatus* - Kerney & Cameron 1979). The six specimens of *D. rotundatus*, usually living on dead wood or bricks

(Cameron & Redfern 1976), were only found on a single living wall which had a flower border at the bottom. *Lauria cylindracea* which tend to favour walls over other habitats (Norris pers. comm.) was only found on green façades, whilst *C. lubrica*, often found on walls with moss, was only found on the angled plastic module system.

These differences and similarities in species composition between GF and LW highlight the complementary nature of green wall systems as potential habitats for snail populations. For snails, LW with their more diverse features might be considered as a completely different habitat than traditional masonry walls, whilst GF might be seen as an intermediate environment. Moreover, snail species might use the green walls differently. Some snail species (such as *Cepaea spp.*) tend to climb vegetation and spend the day immobile on a stem, while others (such as *C. aspersum*) tend to remain on the ground or on the vegetation at the base of the walls during daytime (Chiquet pers. obs.). Unfortunately little information exists on snail communities on masonry walls, urban or otherwise, and prevents further discussion on the subject (Norris pers. comm.).

In dense urban areas, there can be precious little semi-natural habitat for any form of wildlife; the addition of vegetation to walls and roofs of buildings being one of the easiest ways of creating new habitat for animal species to colonise. The technology of green walls is still new and under constant development. The study was primarily on naturally adhering façades and focused mainly on evergreen plants. Other green façade systems, providing plant support for evergreen and deciduous plants away from the wall (e.g. stainless-steel wire-rope), and different living walls systems are also employed. As yet there is a poor understanding of their biodiversity value. Further work, and especially comparative studies of different façade systems and living wall systems, is clearly needed to expand the range of fauna covered, identification of which systems are of greatest value, and how to optimise them for specific groups.

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CHAPTER VI

THE VALUE OF GREEN WALLS FOR URBAN SPIDER POPULATIONS

6. THE VALUE OF GREEN WALLS FOR URBAN SPIDER POPULATIONS

This chapter presents the results from an investigation of the spider fauna of green façades and living walls. The work on the GF data-set has been submitted to Journal of Biological Conservation (Chiquet *et al.* under review 2). The work on the LW data-set will be submitted as a separate manuscript elsewhere.

6.1 ABSTRACT

This study investigated how the presence of vegetation on a wall, its characteristics (vegetation composition, plant richness and density, vegetation surface area, type of foliage (evergreen vs. deciduous), etc.), the surroundings (adjacent land, vehicle and pedestrian traffic) and the seasonality could affect spider communities (i.e. total abundance, species richness, species composition, individual species abundance, sexual maturity, and web design category).

In a first study, spider populations were monitored on twenty-nine green façades paired with equivalent control walls devoid of vegetation, in the summer and autumn of 2011, in Staffordshire, UK. Three collection methods were used: (i) web categorisation (orb, sheet and tangle webs) using visual searching, (ii) manual capture of spiders with a tuning fork, and (iii) vacuum suction sampling. Spider populations were significantly more abundant and diverse on green façades (3065 webs, 2389 spiders, 19 species) than on bare walls (54 webs, 9 spiders, 4 species). Total abundance, individual species abundances and individual web category abundances were greater in the summer than the autumn, whilst species richness (7.6 ±0.64 species on green façades on average) was not affected by the season of capture. Deciduous and evergreen foliage attracted different spider species and web-weavers depending on the season. Visual searching and vacuum suction showed similar abundance when empty webs visually found were included with specimens in the abundance, but, suction sampled more specimens than visual searching. Visual searching and suction sampling showed similar species richness, but sampled different species and age groups.

A second study compared spider populations of twenty-two established living walls and four green screens in the summer of 2012 in Birmingham, London, the Greater London Area, and Stoke-on-Trent, UK. The same collection methods were used as in the first study, resulting in 1993 empty webs, 1112 spiders and 22 species on living walls, and 295 empty webs, 67 specimens and 3 species on green screens. Total abundance, species richness, web-weavers and age groups were differently affected by the type of system, for example, the total abundance and species richness were greater in plastic modules and rockwool units than on green screens. No relationship was found between spider population and vegetation

surface area, whilst spider abundance and richness were positively related to plant richness, plant density, and age of the wall, and negatively related to pedestrian and vehicle traffic volumes.

A third study monitored spider populations on a recently installed living wall and showed the colonisation rate of spider on a new habitat over time. The results suggested that botanical composition affect spider colonisation even before foliage is fully established.

The results highlight the importance of using more than one sampling method for estimating spider species composition. Suction sampling is more appropriate to use on established green façades and living walls, whereas visual searching is more efficient on new living walls. These studies provide a novel insight into the ecology of green walls and their role in improving the ecological functionality of cities. Spiders readily colonise the habitat created by vegetated walls, with green façades and living walls attracting different spider species. Spider distribution will depend on the wall's characteristics, the surroundings (especially human disturbance) and the time of year.

6.2 INTRODUCTION

As predators displaying a wide variety of foraging strategies and habitat requirements (e.g. Gibson *et al.* 1992; Bell *et al.* 2001), spiders, and especially web-spiders are sensitive to changes in habitat composition and structure (Bell *et al.* 2001; Uetz *et al.* 1991). Their prey abundance has been linked with website selection (Olive 1982), indicating a large invertebrate population where spiders are abundant. Thus, establishing the spider fauna of green walls should give important information on the overall biodiversity potential of these habitats. Spider peak time of activity is a species-specific trait and has been shown to be seasonally dependent (Fasola & Mogavero 1995) with guilds having different peaks in summer and autumn (Kisbenedek 1991); as such, the sampling period occurred during these two seasons.

Previous work on green façades and invertebrates showed the importance of using more than one sampling method to estimate abundance, age structure and species richness (Chiquet *et al.* under review 1). Suction samplers are considered to be probably the most useful devices for directly collecting spiders (Dinter 1995; Sunderland & Topping 1995; Samu *et al.* 1997). In addition, web characterisation has been proven to be a cost-effective and easy-to-use method to assess the relative abundance of spiders (Rypstra 1982, Baldissera *et al.* 2004), although it was not always validated by capturing a sample of spiders from webs (see Rypstra 1983; Miller 2001; Gollan *et al.* 2010). Therefore, the following methods were used for direct comparisons: (i) web characterisation in the field, (ii) manual capture of spider specimens (to assess the reliability of the web characterisation), and (iii) an invertebrate suction sampling device.

The study focused on (i) the habitat preferences of spiders on green façades and living walls, in the summer and the autumn and (ii) the sampling effects on spider populations. Spider populations of well-established green façades and living walls were monitored in several locations of England, UK. In addition, a new living wall was set up specifically for this study on the Staffordshire University campus of Stoke-on-Trent, UK.

The study on green façades was designed to test the following hypotheses about their value as a spider habitat:

1. Green façades are expected to have greater spider abundance and species richness than equivalent unvegetated walls.
2. Spider abundance, species richness, species composition, individual species abundance, age groups, and abundance of web categories will be affected by the season of sampling.
3. The type of foliage (evergreen vs. deciduous) is expected to affect spider abundance and species richness, particularly in the autumn. The type of foliage is also expected to have an effect on the age groups and the abundance of web categories. Differences are similarly expected for green façades made of diverse plant species compared to green façades with a single plant species.
4. Vegetation surface area is expected to be positively related to spider abundance and species richness.
5. South-facing walls are expected to have greater spider abundance and species richness than north-facing walls.
6. Different sampling methods will have inbuilt biases, such that spider abundance, species richness, species composition, individual species abundance, age groups, and abundance of web categories will vary with the approach.

The study of established living walls was designed to test the following hypotheses about their value as a spider habitat:

1. Different living wall systems (e.g. rockwool units, plastic modules) are expected to differ in abundance, species richness, age group, and abundance of web categories.
2. Characteristics of the wall, i.e. age of the wall, vegetation surface area, plant density and plant richness, are expected to be positively related to spider abundance, species richness, and abundance of web categories.
3. South-facing walls are expected to have greater spider abundance and species richness than north-facing walls.
4. The environment of the wall, i.e. presence and abundance of surrounding vegetation, vehicle traffic and pedestrian flows are expected affect the spider abundance, species richness, and abundance of web categories using the LW (the abundance of vegetation positively and the vehicle and pedestrian traffic volumes negatively).

5. Different sampling methods will have inbuilt biases such that species composition, individual species abundance, and age structure of spiders would vary with the approach.

The study of a new living wall was designed to test the following hypotheses about their value as spider habitat:

1. Spider abundance and richness will be similar between either end of the living wall and its centre.
2. Spider abundance and richness will be greater in flowering treatment than in non-flowering treatment.
3. Spider abundance and richness will be affected by sampling height.
4. Colonisation rate of spiders will increase over time in density and richness.

6.3 MATERIAL AND METHODS

6.3.1 Study Sites

For detailed information on study sites, please see section 3.1.1 for the green façades, to section 3.1.2 for the established living walls, and to section 3.1.3 for the new living wall.

6.3.2 Web and Spider surveys

For detailed information on spider surveys, please refer to section 3.2.

On each study wall, several surveys were conducted. Between ground level to two metres above ground, the abundance of webs was recorded using a plant mister (capable of reproducing a very fine water spray) to reveal fine webs which might otherwise escape notice (Dennis *et al.* 2001). Each web was categorised into one of the three major architectural groups (Fig. 6.1): orb, sheet and tangle (see Kaston (1948), Burgess & Witt (1976), and Bradley (2012) for more detailed descriptions of each web type). Orb webs correspond to geometric webs, usually round-shaped (sections can be missing), associated primarily with the families Araneidae, Tetragnathidae and Uloboridae (Fig. 6.1a). With this type of web, the spider waits in the middle of the web or has a retreat nearby with a thread linking it to the centre of the web. Sheet webs are two-dimensional with little or no symmetry, usually horizontally orientated with or without a scaffold of threads above (Fig. 6.1b). They are mostly associated with the families Gnaphosidae and Linyphiidae, the spider usually hanging under the horizontal web. A sub-category of sheet webs are funnel webs with a tubular retreat in the middle or on one side where the spider stays, and usually with a denser silk network, associated with the families Agenelidae and Amaurobiidae. Tangle webs are irregular and three-dimensional, associated with the families Dictynidae, Nesticidae and Theridiidae (Fig. 6.1c). The webs were placed into one of the categories based solely on their appearance. Each web was searched for its associated spider by touching the web with a vibrating tuning fork (440 Hz) that mimics buzzing insects trapped in the web and lures the spider out of hiding (Henschel *et al.* 1992; Jakob 2004). When present, spiders were captured for identification in the lab. Spiders observed in the foliage were also captured, using a pooter.

During the same survey visit, a Vortis® suction sampler was used (see section 3.2.2 for further details on the methodology).

Following preservation in 70% ethanol, specimens were counted and identified to species level where possible, using Roberts (1985, 2001) and following nomenclature by Platnick (2013). Spider specimens were classified according to their age and the season of capture. The distinction between juvenile, subadult and adult forms was made on the basis of the maturity of the genitalia (i.e. absent, present but not fully functional, present and functional - Roberts 1985). For spiders not directly sampled on webs, the known web-type characteristic of each family (orb, sheet and tangle), if any, was also used as a categorisation tool. Some specimens were only identifiable to genus level (e.g. *Leptyphantes sp.*), therefore all the specimens of the same genus were considered in the same group when species richness was analysed (Ysnel & Canard 2000; Herrmann *et al.* 2010): for example, *Metellina segmentata* with *Metallina sp.*, *Philodromus aureolus* with *Philodromus sp.*, and *Zygiella x-notata* with *Zygiella sp*., although their individual abundance is given in the results section. Specimens only identifiable to family level were given the family name followed by 'UI' for 'unidentifiable individuals'; they were included in abundance analysis but not in the species richness analysis, unless no other specimens were found in the family (e.g. Thomisidae UI). When too damaged or too juvenile, unidentifiable specimens were discarded from the species richness analysis but considered for the abundance analysis.

6.3.3 Data Analysis

The variables studied were: specimens' abundance, species composition and richness, individual species abundance, total web abundance, web categories abundance (orb, sheet and tangle), and the age structure. Data were standardised to 1m² unless stated otherwise.

On green façades, the factors investigated were the effects of: vegetation on walls (n=29) compared to the paired control (i.e. bare walls, n=29), seasonality (summer vs. autumn), sampling method, the type of foliage (evergreen (n=23) vs. deciduous (n=6)), the vegetation diversity (whether the green wall consisted of a single plant species (n=19) or many species (n=10)), the vegetation surface area, and the aspect (categorised on the basis of the four cardinal directions and the four intercardinal directions). For detailed information on the GF characteristics, please see Table 3.1.

On the established living walls, the direct factors investigated were: effect of different green wall systems (6 different living wall systems (n=22), see section 3.1.2) and green screens (n=4), effects of plant density and plant richness (counting the different genera and not the different cultivar, see Appendix 5), and effects of vegetation surface area, wall aspect, and wall age. The indirect factors investigated were: differences between cities (Birmingham vs. London), changes in abundance and richness over time (four samples were taken with fortnightly intervals), effect of the presence and abundance of surrounding vegetation, and the effects of pedestrian and vehicle traffic volumes. For detailed information on the LW characteristics, please see Table 3.2.

On the new living wall, the factors investigated were the height (low vs. high), the vegetation composition categories (flowering vs. non-flowering) and changes in abundance and richness over time (five samples taken with fortnightly intervals).

To enable comparison between sampling methods, spider data were standardised to 1 m² of vegetation (unless stated otherwise) and comparative analyses were carried out in the following groups: (i) specimen abundance, species richness and species composition in manual vs. suction samples, (ii) abundance of spider web categories using visual searching vs. suction (including the empty webs visually found), and (iii) total abundance (empty webs and specimens) via visual searching vs. specimen abundance via suction. For detail of the statistical tests, see section 3.3. Analysis were carried out on the mean abundances and richnesses found on wall for each visit (with three samples in the summer 2011 and three samples in the autumn 2011 on GF, and four samples in the summer 2012 for LW).

6.4 RESULTS – VALUE OF GREEN FAÇADES FOR SPIDERS

6.4.1 Spider population in green façades compared to bare walls

Using visual searching, 4568 spider webs were found on green façades; of these, 3065 webs were empty and 1503 (32.9%) had spiders found on them. An additional 164 spiders were found on vegetation. Using suction sampling, 722 spiders were captured. overall, nineteen species of spider were identified from nine families; spiders from a further four families could not be identified to species. The most species-rich families were Linyphiidae (6 species), Araneidae (4 species) and Theridiidae (4 species). The families with the greatest abundance were the orb-weaving Araneidae (47.1%) and the sheet-weaving Amaurobiidae (24.4%). Six of the spider species (31.6%) were singletons and four families (30.8%) were represented by fewer than five individuals. In addition to these spiders, 30 opiliones and over 500 Acari (Trombidiformes and Ixodida) were captured; they were not included in the analysis of abundance and richness. In total, 429 specimens (18.0%) could not be identified due to developmental stage or damage (and were only included in analysis of abundance). A further 12.8% could only be identified to family level and are termed 'UI' ('unidentifiable individuals').

On bare walls, 54 webs were visually found, none of which contained spiders. Using suction sampling, 9 spiders were found belonging to four species (*A. similis*, *A. diadementus*, *S. bipunctata*, *Z. x-notata*). No opiliones or acari were captured.

The presence of vegetation on walls significantly affected spider abundance compared to their paired control ($H_{(4)}$= 105.73, p<0.001), whether by visual searching (z=-4.86, n=29, p<0.001) or by suction (z=-4.93, n=29, p<0.001) (Fig. 6.2). No comparative analysis was carried out on species richness due to the small richness on bare walls, but it was clear from the data that many more species were found on green facades compared to bare walls (19 and 4 respectively). The following analysis refer to differences between green façades attributes only, to establish if different characteristics (such as seasonality or the type of foliage) had any influence on spider abundance and age structure, species richness and composition, individual species abundance, and abundance of spider web categories.

6.4.2 Seasonality effect on spider richness and species composition

The average species richness was approximately eight species by wall (7.6 ±0.64) and was not affected by season or sampling method (see Table 6.1). However, seasonality altered the composition at both family- and species-level on green façades. Four species and 2 families (*A. similis*, *E. ovata*, *T. domestica*, *Zygiella sp.*, Amaurobiidae, Linyphiidae) were significantly more abundant in the summer than the autumn and three species and one family (*D. uncinata*, *E. dentipalpis*, *W. cuspidate*, Nesticidae) were not present in autumn (Table 6.2). Two genera (*Philodromus sp.*, *Clubiona sp.)* were significantly more abundant in the autumn than the summer; and five species and one family (*Bathyphantes sp.*, *C. terrestris*, *L. patagiatus*, *P. pallens*, *S. bipunctata*, Thomisidae) were not present in summer (Table 6.2).

6.4.3 Spider composition in visual searches (web counts and manual sampling)

Among the specimens captured with a tuning fork, 227 specimens (13.6%) were not identifiable to family or species level. Specimens were significantly more abundant during the summer than the autumn with or without considering those that were unidentifiable, whilst the species richness was not affected by season (Table 6.1). In total, thirteen species from seven families were captured with the tuning fork; spiders from a further three families could not be identified to species (see Table 6.3 for further details). The most abundant families were the orb-weaving Araneidae (42.8%), and the sheet-weaving Amaurobiidae (38.8%) and Agelenidae (12.3%).

Adult spiders were more abundant than juvenile spiders when data from both seasons were aggregated ($z=-4.35$, $n=29$, $p<0.001$) and in each season (see Fig. 6.3 and Table 6.4 for further details). The abundances of both adults and juveniles were significantly greater in the summer than in the autumn (Fig. 6.3, Table 6.4).

Web-weavers responded differently to the season of sampling using visual searching (Fig. 6.4). In the summer, sheet-weavers were significantly more abundant than orb-weavers and the abundance of tangle-weavers was intermediate, whilst in the autumn, the three web categories were of similar abundance (see Fig. 6.4 and Table 6.5 for further details). Sheet-weavers were more abundant in the summer than the autumn, whilst orb-weavers and tangle-weavers were not affected by the season of sampling (Fig. 6.4, Table 6.5).

6.4.4 Spider composition in suction samples

Using vortis suction, 323 specimens (44.7%) were not identifiable to family or species level due to damage or developmental stage. With or without considering unidentifiable specimens, spiders were more abundant in the summer than the autumn, whilst seasonality had no effect on species richness (Table 6.1). In total, eighteen species from eight families and a further three families with no identifiable specimens were captured by suction (see Table 6.3 for further details). The most abundant families were the orb-weaving Araneidae (49.1%), the tangle-weaving Theridiidae (11.1%), the hunter Philodromidae (9.1%) and the sheet-weaving Linyphiidae (7.5%).

Via suction capture, juvenile spiders were more abundant than adult spiders when data from both seasons were aggregated ($z=-5.17$, $n=29$, $p<0.001$), and in each season (see Fig. 6.3 and Table 6.4 for further details). The abundance of juveniles was similar in the summer and the autumn, but adults were more abundant in the summer than in the autumn (Fig. 6.3, Table 6.4).

Web-weaving spiders responded differently to the season of sampling using suction (Fig. 6.4). More orb-weavers were captured than sheet- and tangle-weavers when data from both seasons were aggregated ($z=-4.62$, $n=29$, $p<0.001$ and $z=-4.90$, $n=29$, $p<0.001$ respectively), and in each season (see Fig. 6.4 and Table 6.5 for further details). In addition, each web category was more abundant in the summer than in the autumn although the effect was not significant for tangle-weaving spiders (Fig. 6.4, Table 6.5).

6.4.5 Efficiency of sampling approach

Vortis suction and web counts sampled similar abundances of spiders, when data from both seasons were aggregated, and in each season (Table 6.1). However, when only specimens captured by tuning fork were considered (i.e. empty webs were removed from the visual searching surveys), more spider specimens were captured by suction than visually observed, with or without considering unidentifiable specimens when data from both seasons were aggregated, and in each season (see Table 6.1 for further details).

Species richness was not affected by the sampling method when data from both seasons were aggregated, or in each season (Table 6.1), but species composition and individual species abundance changed (Table 6.3): three species and two families were exclusively found via visual searching *(D. unicinata*, *L. triangularis*, *M. segmentata*, Dictynidae, Thomisidae), whilst seven species and two families were exclusively captured via suction (*Bathyphantes sp.*, *Clubiona sp.* (including *C. terrestris*), *E. dentipalpis*, *K. tincta*, *P. pallens*, *Philodromus sp*. (including *P. aureolus*), *W. cuspidata*, Nesticidae, Philodromidae, Salticidae). Moreover, three species and two families were captured significantly more frequently manually than caught by suction *(A. similis*, *L. triangularis*, *T. domestica*, Agenilidae, Amaurobiidae), whilst two species and five families were significantly more abundant in suction samples than manual samples (*Philodromus sp.* (including *P. aureolus*), *Zygiella sp.* (including *Z. x-notata*), Araneidae, Gnaphosidae, Linyphiidae, Philodromidae, Theridiidae). More unidentifiable specimens (due to damage and/or developmental stage) were captured via suction than manually (Table 6.3).

Juveniles were significantly more abundant in suction samples than found using visual observation when data from both seasons were aggregated ($z=-4.70$, $n=29$, $p<0.001$), in the summer and in the autumn; whilst adults were not affected by the type of sampling method when data from both seasons were aggregated, and in each season (Fig. 6.3, Table 6.4).

Orb-weavers were significantly more abundant in suction surveys than by visual searching when data from both seasons were aggregated ($z=-2.99$, $n=29$, $p=0.003$), and in each season (Fig. 6.4, Table 6.5). Conversely, sheet-weavers and tangle-weavers were found to be more abundant using visual searching than suction sampling when data from both seasons were aggregated ($z=-2.37$, $p=0.018$ and $z=-2.02$, $p=0.044$ respectively), and in each season (although not always significantly, see Table 6.5).

6.4.6 Effect of foliage type on capture rates and on seasonality

Walls were covered with either deciduous or evergreen foliage (6 and 23 sites respectively). Total abundance (empty webs and specimen) and specimen abundance using visual searching were compared to specimen abundance via suction.

Using visual searching, total abundance and specimen abundance were greater in evergreen foliage than in deciduous foliage, when data from both seasons were aggregated ($z=-2.08$, $p=0.031$; $z=-2.19$, $p=0.026$ respectively), and in each season (Fig. 6.5a and 6.5b respectively and Table 6.6). Using suction sampling, specimen abundance was greater in evergreen foliage than in deciduous foliage in the autumn but not when data from both seasons were aggregated or in the summer (see Fig. 6.5, Table 6.6).

Using visual searching, total abundance and specimen abundance were greater in the summer than in the autumn in evergreen foliage, whilst in deciduous foliage, seasonality had no effect on total and specimen abundances. Via suction sampling, seasonality had no effect on specimen abundance in evergreen foliage and in deciduous foliage (see Fig. 6.5).

In deciduous foliage, as in evergreen foliage, total abundance via visual searching was similar to specimen abundance via suction, in the summer and in the autumn (Fig. 6.5a, Table 6.6). Conversely, in deciduous foliage, as in evergreen foliage, specimen abundance via visual searching was lower than specimen abundance via suction in each season (Fig. 6.5b, Table 6.6).

The total species richness was greater in evergreen foliage than in deciduous foliage for both sampling methods and both seasons (see Fig. 6.6, Table 6.7 for further details). However, the type of foliage did not affect species richness in each season for both sampling methods; similarly, estimation of species richness was similar using both sampling methods in each season (Fig. 6.6, Table 6.7).

The type of foliage had no effect on the abundance of adult spiders, as on the abundance of juvenile spiders, when data from both seasons were aggregated or in each season, using both sampling method (p>0.05).

Abundances of web categories were not significantly affected by the type of foliage using both sampling method, when data from both seasons were aggregated or in each season (p>0.05).

6.4.7 Effect of plant diversity, vegetation surface area and aspect on spider populations

Vegetation diversity, i.e. whether the green wall consisted of a single plant species (n=19) or many species (n=10), had no significant effect on spider abundance and richness using visual searching (p=0.126, p=0.512 respectively) or via suction sampling (p=0.232, p=0.187 respectively).

Vegetation surface area of green façades showed no significant relationship with spider abundance, species richness or abundance of web categories (p>0.05).

The aspect of the green façades, categorised either on the basis of the four cardinal directions or on the basis of the four cardinal plus the four intercardinal directions, had no significant effect on spider abundance, species richness or abundance of web categories (p>0.05).

6.5 RESULTS – VALUE OF ESTABLISHED LIVING WALLS FOR SPIDERS

6.5.1 Spider population on established living walls

Overall, in Birmingham and London, 1993 spider webs were visually found on the living walls; of these, 1649 were empty and 344 (17.2%) had spiders on them. Using suction sampling, 768 spiders were captured on living walls. Twenty-two species of spider from eight families were identified; an additional family had specimens not identifiable to species level (see Table 6.8 for further details). The most species-rich families were Linyphiidae (9 species) and Theridiidae (4 species). The families with the greatest abundance were the orb-weaving Araneidae (32.9%) and the sheet-weaving Linyphiidae (20.4%). Overall, 11 of the spider species (50.0%) were singletons and 6 families (66.7%) were represented by fewer than five individuals. In addition to these spiders, 20 opiliones and 80 Acari (Trombidiformes and Ixodida) were captured; they were not included in the analysis of abundance and richness.

On green screens, 295 empty webs and 67 specimens belonging to three species and three families were sampled (Table 6.8). In addition, 5 opiliones and 67 Acari (Trombidiformes and Ixodida) were captured; they were not included in the analysis of abundance and richness.

Due to damage or developmental stage, 32.7% of the specimens on living walls could not be identified (and were only included in the analysis of abundance). A further 23.8% of the specimens could only be identified to family level, and are termed 'UI' ('unidentifiable individuals'). On green screens, 7.5% of the specimens could not be identified, and 12.0% of the specimens could only be identified to family level.

6.5.2 Efficiency of sampling approach

Both visual searching and suction sampling were used and data followed exactly the same trends for the two sampling methods, although statistical tests were less significant with visual searching. In addition, all species observed *in situ* were captured by suction. Following this observation, only suction sampling results are reported here (unless stated otherwise).

6.5.3 Total species richness, web-weavers and age groups

The average species richness was eight species by living wall (7.7 ±0.5) and one species by green screen (0.8 ±0.13). The mean abundance by LW of juveniles (13.2 ±2.82) were greater than subadults (4.0 ±0.60) ($z=-2.60$, $n=22$, $p=0.009$) but similar to adults (8.1 ±1.60) ($z=-1.23$, $n=22$, $p=0.218$). The period of sampling did not significantly affect the size of the age groups ($p>0.05$). On living walls, the web-weaving groups were, in descending order of mean abundance: sheet-weavers (4.8 ±0.58), tangle-weavers (1.1 ±0.19), and orb-weavers (0.4 ±0.74) (sheet- vs. tangle-weavers: $z=-9.43$, $n=22$, $p<0.001$, sheet- vs. orb-weavers:

$z=-4.17$, $n=22$, $p<0.001$, tangle- vs. orb-weavers: $z=-6.90$, $n=22$, $p<0.001$). Because differences were so significant, no further comparative analysis was carried out between the three web categories.

6.5.4 Effect of the LW system on spider populations in suction samples

Only one type of LWS, the angled plastic module, was present in both London and Birmingham. The analysis of this system with 13 walls (8 in Birmingham and 5 in London) showed no differences in abundance or in species richness between the two cities ($z=-0.91$, $n_1=8$, $n_2=5$, $p=0.362$ and $z=-1.10$, $n_1=8$, $n_2=5$, $p=0.269$). Following this, results were aggregated from the two cities.

The six different types of LW system (see section 3.1.2 for further details on the studied systems) significantly affected the abundance and species richness ($H_{(5)}= 24.63$, $p<0.001$; $H_{(5)}= 18.60$, $p=0.002$ respectively). The three types of rockwool systems showed no differences for abundance or species richness ($H_{(2)}= 1.09$, $n=6$, $p=0.580$ and $H_{(2)}= 1.86$, $n=6$, $p=0.394$ respectively) and were subsequently aggregated. Similarly, the green screens in London and Stoke-on-Trent were comparable in spider abundance and species richness ($z=-0.69$, $n=4$, $p=0.645$ and $z=-0.387$, $n=4$, $p=0.798$ respectively) and were also aggregated. Then, comparative analysis were carried out on green screens, plant pots, horizontal plant box, rockwool unit and angled plastic module systems.

Spider abundance, similar in rockwool units and angled plastic modules, was significantly greater in these two systems than on green screens, plant pot and horizontal plant box systems, all three latter systems being of similar abundances (see Fig. 6.7a and Table 6.9 for further details). Species richness significantly varied by system type, with an increase from green screen and plant pot system, through rockwool units to angled plastic modules, whilst species richness in horizontal plant boxes was similar to all the other systems (see Fig. 6.7b, Table 6.9 for further details).

Age groups were affected differently by the type of system. Only subadults were found in plant pots. In rockwool systems, the mean abundance of juveniles (3.3 ±0.77) was significantly greater than subadult abundance (1.2 ±0.36) or adult abundance (1.2 ±0.30) ($z=-2.60$, $n=6$, $p=0.009$; $z=-2.40$, $n=6$, $p=0.016$ respectively); whilst in angled systems, juveniles (5.1 ±0.87) and adults (3.5 ±0.46) were both more abundant than subadults (1.2 ±0.25) ($z=-4.33$, $n=13$, $p<0.001$; $z=-4.39$, $n=13$, $p<0.001$ respectively). The three age groups had the same abundance on green screens and horizontal plant box systems (less than one specimen of each age group was found on average by wall and sample).

The abundance of the spider web categories varied between the different systems (Fig. 6.8). The orb-weavers were significantly more abundant on green screens than in the horizontal plant boxes, rockwool units or angled plastic modules, whilst the abundance in plant pot systems was similar to that in all the other systems and the green screens (see Fig. 6.8a and Table 6.10 for further details). The sheet-weavers abundance, similar in horizontal plant boxes, rockwool units and angled plastic modules, was greater in these three systems than in the green screens and the plant pot systems, both these latter two being of similar abundances (Fig. 6.8b, Table 6.10). The tangle-weavers were more abundant in angled plastic modules than in all the other LW systems and the green screens (Fig. 6.8c, Table 6.10).

6.5.5 Effect of sampling period on spider abundance and species richness in suction samples on LW

The period of sampling showed different effects in Birmingham and London (Fig. 6.9). In the nine LW in Birmingham, abundance and species richness showed a sawtooth-like pattern over time (Fig. 6.9a,c). Spider abundance was significantly lower in the first sample than in the three following samples of similar abundance (see Fig. 6.9a and Table 6.11 for further details). The first sample was significantly less rich in species than the second sample; whilst the 3rd and 4th samples were similar in species richness to the 1st and 2nd samples (Fig. 6.9c, Table 6.11). In London, abundance and species richness were similar during the first three samples (from June to August), and then increased during the fourth sample, although no significant differences were found between the samples (Fig. 6.9b,d, Table 6.11).

6.5.6 Effect of the LW characteristics on spider populations

The living walls varied in age, in vegetation surface area, in plant density and richness and in aspect (see Table 3.2 and Appendix 5).

The age of the walls was positively related to spider abundance and the species richness (R^2=0.45, $F_{1,21}$=19.94, p<0.001; R^2=0.52, $F_{1,21}$=25.86, p<0.001 respectively - Fig. 6.10a,b). Similarly, the age of the walls was positively related to the abundance of sheet-weavers and tangle-weavers (R^2=0.352, $F_{1,21}$=13.06, p=0.001; R^2=0.55, $F_{1,21}$=29.27, p<0.001 respectively), whilst not with orb-weavers abundance (p=0.540) (Fig. 6.10c,d,e).

Vegetation surface area of living walls showed no significant relationship with spider abundance, species richness or abundance of web categories (p>0.05).

The plant density on living walls was positively related to spider abundance and species richness (R^2=0.46, $F_{1,21}$=20.70, p<0.001; R^2=0.29, $F_{1,21}$=9.98, p=0.004 respectively - Fig. 6.11a,b). In addition, the plant richness (counting the different genera) was positively related to spider abundance and species richness (R^2=0.30, $F_{1,21}$=9.62, p=0.005; R^2=0.35, $F_{1,21}$=11.87, p=0.002 respectively - Fig. 6.11c,d). Spider web groups were affected differently by the plant richness and density (Fig. 6.12). Orb-weavers were negatively related to plant density (R^2=0.15, $F_{1,21}$=4.34, p=0.048) but not related to plant richness (p=0.074) (Fig. 6.12a,b). Conversely, plant density and plant richness were positively related to sheet-weavers (R^2=0.39, $F_{1,21}$=15.28, p=0.001; R^2=0.33, $F_{1,21}$=11.92, p=0.002 respectively - Fig. 6.12c,d) and tangle-weavers (R^2=0.44, $F_{1,21}$=18.97, p<0.001; R^2=0.22, $F_{1,21}$=6.74, p=0.016 respectively - Fig. 6.12e,f).

The aspect of the living walls, categorised either on the basis of the four cardinal directions or on the basis of the four cardinal plus the four intercardinal directions, had no significant effect on spider abundance, species richness or abundance of web categories (p>0.05).

6.5.7 Effect of adjacent land, vehicle and pedestrian traffics on spider abundance and species richness on LW

The closeness and abundance of vegetation surrounding the living walls, the vehicle traffic volumes and the pedestrian traffic flows were categorised into four categories (from 0 'none' to 3 'high', see Table 3.2).

There was a significant negative relationship between vehicle traffic volume and spider abundance via visual searching (R^2=0.21, $F_{1,21}$=4.99, p=0.038), but no relationship was found using suction (p>0.05). No relationships were found between vehicle traffic volume and species richness or abundance of web categories, either using suction or visual searching (p>0.05).

The pedestrian traffic flow was negatively related to spider abundance and species richness (R^2=0.48, $F_{1,21}$=20.61, p<0.001; R^2=0.12, $F_{1,21}$=12.33, p=0.001 respectively - Fig. 6.13a,b). Significant relationships were found between pedestrian traffic volumes and web-weavers. The relationship was positive with orb-weavers (R^2=0.26, $F_{1,21}$=8.65, p=0.007 - Fig. 6.13c) and negative with sheet-weavers and tangle-weavers (R^2=0.21, $F_{1,21}$=6.36, p=0.019; R^2=0.28, $F_{1,21}$=9.17, p=0.006 respectively - Fig. 6.13d,e).

The surrounding vegetation did not significantly affect spider abundance, species richness or abundance web categories (p>0.05).

6.6 RESULTS – COLONISATION OF NEW LIVING WALLS BY SPIDERS

6.6.1 Spider population on a new living wall

On the recently installed new wall, 63 spiders and 199 empty webs were recorded over the 4-sample period from July to August 2012. A first sample was taken in June 2012, no web or spider specimen were found using both visual searching and suction, apart from one *Araneus diadementus* in a suction sample. The captured specimens belonged to the family Araneidae (orb-weavers): *Araneus diadementus*, *Zygiella x-notata* and the family Linyphiidae (sheet-weavers): *Tenuiphantes tenuis.* Only empty tangle webs were found on the living wall, but no tangle-weavers.

Due to damage or developmental stage, 28.6% of the specimens could not be identified, and were only included in the analysis of abundance. A further 17.5% of the specimens could only be identified to family level, and are termed ‘UI’ (‘unidentifiable individuals’). In addition to spider specimens, one opilion and seven Acari (Trombidiformes and Ixodida) were captured; they were not included in the analysis of abundance and richness.

Of the 63 spider specimens, 22 were caught on their web and 41 captured by suction; due to the small abundance, no direct comparison was made between the two sampling methods.

6.6.2 Effect of height and vegetation composition on spider abundance

No edge effects were evident on the new living walls, as spider abundance was similar on the panels at either end of the wall and on the panels in the centre of the wall (visual searching: p=0.946; suction: p=0.634, see Fig. 3.3 for further details on the wall design). The spider data were then aggregated by plant treatment (flowering treatment vs. non-flowering treatment) and height (low vs. high), in four groups.

Spider abundance was not affected by height using visual searching or suction, either when data from both treatments were aggregated or in each plant treatment. Vegetation composition, on the other hand, affected spider population. Via visual searching, spider abundance was greater in non-flowering treatment than in flowering treatment, when data from both heights were aggregated (z=-3.14, n=7, p=0.002), in the lower blocks and in the higher blocks (see Fig. 6.14a and Table 6.12 for further details). Conversely, in suction samples, spider abundance was greater in flowering treatment than in non-flowering treatment when data from both heights were aggregated, and in each height although not significantly (Fig. 6.14b, Table 6.12).

Height did not affect abundance of web categories using visual searching, or using suction (see Fig. 6.15a,b and Table 6.13 for further details). By visual searching, orb- and sheet-webs were of similar abundance in lower blocks and in higher blocks; both were more abundant than tangle-webs (Fig. 6.15a, Table 6.13). By suction sampling, orb-weavers were less abundant than sheet-weavers in lower blocks while being of similar abundance in higher blocks (Fig. 6.15b, Table 6.13). Vegetation composition affected differently abundance of web categories (Fig. 6.15c,d and Table 6.13). Using visual searching, more orb-webs and sheet-webs were found in non-flowering treatment than flowering treatment, whilst the abundance of tangle-webs was not affected by vegetation composition (Fig. 6.15c, Table 6.13). Via suction, abundances of orb-weavers and sheet-weavers were similar in non-flowering treatment and in flowering treatment (Fig. 6.15b, Table 6.13). In non-flowering treatment and in flowering treatment, orb-weavers were as abundant as sheet-weavers for both sampling methods; both orb- and sheet-web were more abundant than tangle-webs using visual searching (Fig. 6.15c,d and Table 6.13).

When the effects of both heights and both vegetation compositions were analysed, there were no significant differences between and within the different web category abundances due to the relatively high variability between samples for both sampling methods (p>0.05).

6.6.3 Colonisation over time

Spider abundance increased significantly over time from the beginning of July to the end of August using visual searching or suction, with a prior sampling session in June (sample 1) where no specimens or webs were found apart from one *A. diadementus* via suction (see Fig. 6.16 and Table 6.14 for further details). By visual searching, total abundance (empty web and specimen) reached a peak during the 4th sample (mid-August), and was significantly lower in the second sample than in the following ones (Fig. 6.16a, Table 6.14). By suction, specimen abundance increased incrementally over time, with the 5th sample significantly different from the first ones (Fig. 6.16b, Table 6.14).

6.7 DISCUSSION

The present study showed that (i) spiders will preferentially use vegetation growing on vertical surfaces rather than bare surface and that (ii) the green walls attributes will affect spider communities depending on the time of year. The methodology used was able to sample both diurnal species which are active during the sampling period, and nocturnal ones that could be found hidden in the foliage.

6.7.1 Value of green façades for spiders

6.7.1.1 Species composition on green façades

On green façades, the numerically dominant species were *A. similis* (24.1%), *A. diadementus* (16.2%) and *Z. x-notata* (10.6%); they contributed largely to the dominance of the families Amaurobiidae and Araneidae in samples. This was not surprising as they are two families with a large number of species with wide distributions (Platnick 2013). This dominance by only a few species is typical for agroecosystems (Ludy & Lang 2004) and is indicative of a relatively high-intensity management of sites (Bell *et al.* 2001).

Spider communities on green façades predominantly comprised common species, but included two interesting taxa: *L. patagiatus* (only a few incidences in Britain as a whole and only recorded in the Lichfield area in Staffordshire, although widespread in western and central

Europe - Slawson pers. comm.) and *D. uncinata* (uncommon species found predominantly in woodland, widespread in England but with only few records from the south-west - British Arachnological Society 2013; Slawson 2013). Among the species found on green façades, *A. similis*, *A. diadementus*, *S. bipunctata*, *T. domestica* and *Z. x-notata* are usually monitored around or in buildings (British Arachnological Society 2013), which may be related to their presence on the bare walls (apart from *T. domestica*). *C. terrestris*, *E. ovata*, *E. dentipalpis*, *K. tincta*, *L. triangularis*, and *N. montana* are usually found in low vegetation; *P. pallens* usually constructs its web at intermediate heights, on evergreen shrubs or herbaceous vegetation, whilst *D. uncinata* is usually found in high vegetation in scrub, hedgerows or woodlands (British Arachnology Society 2013). *A. diadementus*, *L. patagiatus*, and *W. cuspidata* occur in a variety of habitats, from woodlands to open country. *M. segmentata* and *P. aureoles* are found in a variety of wooded habitats including broad-leaved, mixed and coniferous woods, hedgerows and scrub. Thus, most of the spider species found on green façades are widespread, however, as they are all more commonly observed in a variety of habitats, their presence on green walls show the attractiveness of this urban environment structure for different habitat groups.

6.7.1.2 Effect of seasonality on species composition on green façades

Confirming the hypothesis, both juveniles and adults, spiders were more abundant in the summer than in the autumn, mainly due to the greater abundance of orb- and sheet-weavers than tangle-weavers. Some families and species were only, or more, abundant in the summer (Amaurobiidae, Linyphiidae and Nesticidae; *A. similis*, *E. dentipalpis*, *E. ovata*, *D. uncinata*, *T. domestica*, *W. cuspidata* and *Zygiella sp.*); whereas some were only, or more, abundant in the autumn (Thomisida; *Bathyphantes sp.*, *Clubiona sp.*, *L. patagiatus*, *S. bipunctata*, *P. pallens*, *Philodromus sp*. and *S. bipunctata*). Seasonal changes can lead to a change of habitat structure and prey activity, two factors to which orb- and tangle-weavers have been shown to respond to with greater intensity than sheet-weavers (Rypstra 1983). However, whilst the species composition changed, the total species richness was the same in each season indicating that green façades are as attractive to spider communities in the summer as in the autumn.

6.7.1.3 Influence of the vegetation characteristics on spider population

As expected, more spiders were found in evergreen foliage than in deciduous foliage, especially in the autumn (whilst the latter had started to change colour, leaves had not yet started to fall). However, there were relatively few study sites with deciduous foliage, and it is possible that the validity of the findings could be questioned despite the significance of the results. Nevertheless, the results are in line with expectations that foliage density would be important for spiders in the provision of shelter and protection, especially in the autumn (Fasola & Mogavero 1995; Bell *et al.* 2001; Blamires *et al.* 2007).

Green Façades with diverse plant species did not show greater spider abundance or species richness than green façades with monoculture despite previous findings on other ecosystems (e.g. Greenstone 1984; Fasola & Mogavero 1995; Rypstra *et al.* 1999; Mcnett & Rypstra 2000; Blamires *et al.* 2007). Whilst multi-species environments are usually expected to have a greater spider species diversity (Rypstra *et al.* 1999), these results run counter to the generalisation traditionally made about the response of spider diversity to increased plant richness (see Siemann 1998 and references therein). This may be because although some façades were made of diverse species, the polyculture of some of the site might have been too small to play a role, or because the overall biomass was similar between sites, either made of a single or diverse species (Siemann 1998). This finding may also be related to the dominant monoculture nature of the study sites (mainly *Hedera helix* façades).

6.7.2 Comparison of the sampling methods

More identifiable spider specimens (both hunting and web-weavers) were captured using suction than by visual searching. Even when unidentifiable specimens were included in abundance, and despite their greater percentage in suction samples (44.7%) than in visual searching samples (13.6%), more specimens were captured using suction than visually observed. However, when empty web abundance was added up with specimen abundance via visual searching, the total abundance was similar to the specimen abundance by suction.

Although the techniques employed identified a similar species richness on a per wall basis, the species compositions were different (Table 6.3). For example, hunting spiders like Salticidae were only captured by suction and not visually observed (see Wade *et al.* 2006). The sampling techniques also affected the age groups captured. More juveniles were sampled using suction, and more adults using manual sampling. Where visual searching could have missed small specimens, as small and hidden spiders are likely to be overlooked by the observer (Ludy & Lang 2004), suction was powerful enough to remove them from their retreats and was proven to be more effective at collecting small invertebrates (<5cm) than large ones (Doxon *et al.* 2011; Chiquet *et al.* under review 1). In addition, the tuning fork could be mistaken for an approaching predator (Nakata 2008) and consequently small-bodied species and juvenile spiders may hide when it is used during visual searching. Thus, the difference in the efficiency of the sampling methods may be explained by the predator-avoiding strategies of the different spider species (Amalin *et al.* 2001), but also by the different habitat strata the two techniques sampled (Dobyns 1997). Visual searching sampled communities mostly present on the outer surface of the foliage, whereas suction captured both on the foliage surface and within it. As such, suction sampling was shown to be able to capture arthropods hiding in leaf strata where no specimens are visually found (Dennis *et al.* 2001).

The influence of different active sampling methods on spider abundance and the estimation of species richness have been well documented by Clausen (1988), Churchill (1993), Sunderland *et al.* (1995), Oliver & Beattie (1996), Dobyns (1997), Florez (1998), Churchill & Arthur (1999), Norris (1999), Toth *et al.* (2004), Kapoor (2006), Guevara & Aviles (2009). However, only a few studies looked at the sampling effect of a gasoline-powered vacuum and visual searching (Sunderland *et al.* 1995; Amalin *et al.* 2001), usually comparing them to other techniques (Sunderland *et al.* 1995, Wade *et al.* 2006), and only looking at specimen abundance by visual searching, not web counts or web characterisation. Thus, in lime orchards and cotton fields, manual sampling was shown to sample more spiders overall and more hunting spiders than suction sampling, but similar abundance of web-weavers (Amalin *et al.* 2001, Wade *et al.* 2006). The difference of results in these studies compared to this study, where suction sampling appears to be more efficient at capturing spiders than visual searching, may be related to the different vegetation strata and the vertical structure of the study sites. Due to the vertical nature of green walls and their limited horizontal structure, typical sampling techniques such as beating or sweep net sampling are of limited use. Vacuum systems such as suction are, however, ideal in such contexts and appear to sample spider communities effectively, capturing both web-based and hunting species (Dennis *et al.* 2001). Manual sampling with the use of tuning fork was used in this study, to verify the diversity of species on site, and to link the web abundance *in situ* with spider abundance and richness of the suction samples.

Using visual searching, sheet-weavers were more abundant than orb- and tangle-weavers, whereas suction captured more orb-weaving spiders than sheet- and tangle-weavers. As suction sampled within the foliage (as opposed to the outer surface only by visual searching), these results may be related to the plant architecture, and to age-related activity: the study sites were mainly made of ivy plants which become quite woody under the foliage when the plant reaches a certain level of maturity (Metcalfe 2005). The woody structure creates an ‘understory’ habitat where invertebrates may move while being protected. This may explain the predominance of orb-weaving spiders underneath the foliage, as they need a more complex architecture (branch, leaves, etc.) to build larger interception webs compared to sheet- and tangle-web spiders (Mcnett & Rypstra 2000). In addition, orb-weaving spiders captured by suction were mostly juveniles which hide under foliage to avoid predation and are less likely to move in open habitat (Blamires *et al.* 2007). Consequently, this study suggests that web characterisation may be used to assess the relative abundance of spiders only when the vegetation is not too dense.

The results highlight the advisability of using more than one method to achieve a good estimate of spider species richness of green walls. While web characterisation alone appears to gives a good estimate of the total spider abundance, it should be used in conjunction with manual sampling to estimate species richness (although it may underestimate hunting spider richness, and other foliage-dwelling spiders - Ludy & Lang 2004). As shown in this study and Sunderland & Topping (1995), the best approach in terms of reliability for comparing spider populations between sites and seasons, appears to be the joint use of suction sampling and visual sampling. However, the visual sampling method is more time-consuming (because it has a visual searching component and a manual component - to capture specimens) than the suction approach which, on its own, appears to give a good estimate of both abundances, species richness and species composition (see also Borges & Brown 2013). As such, if time is a constraint, suction alone is a suitable technique for the estimation of spider abundance and species richness on green walls.

6.7.3 Value of established living walls for spiders

6.7.3.1 Species composition on established living walls

Spider species found on LW were all generalist spiders, and little information on the quality of the habitat may be ascertained through them. The more abundant species were *A. diadementus* (22.8%), *T. tenuis* (13.4%) and *Z. x-notata* (9.2%), and they contributed largely to the dominance of the families Araneidae and Linyphiiidae in samples. As on green façades, this dominance of only a few species is typical for agroecosystems (Ludy & Lang 2004) and is indicative of a relatively high-intensity management of sites (Bell *et al.* 2001). Spider communities on living walls were predominantly comprised of common and widespread species. *T. flavipes* and *T. tenuis* are pioneer species; with *E. atra*, they are ubiquitous disturbed-habitat specialists and were shown to be among the most frequently occurring and abundant species in the largely disturbed and eutrophic habitats of the London area (Milner 2000). *E. ovata*, *E. latimana*, *L. triangularis* are spiders of open habitats containing low broad-leaved vegetation such as road verges and gardens, whilst *A diadementus and P. pallens* usually construct their webs on evergreen shrubs or herbaceous vegetation of all heights (British Arachnology Society 2013). *E. aphana*, *E. tuberculata*, *P. cespitum* are usually found in heathland, hedgerows, scrub and wooded habitat, whilst *L. leprosus*, *T. melanurum and Z. x-notata* are synanthropic species, usually constructing their webs in and around buildings (British Arachnology Society 2013). *M. nebulosus* and *Palliduphantes ericaeus* are usually occurring in damp habitats and require fairly humid conditions (British Arachnology Society 2013) and, here, they were found in plant pots and rockwool units walls. The plants on one of the rockwool units wall were not covering the entire surface, partly due to a fault in the irrigation; the bare surface thus created the open, warm habitat preferred by *C. bicolor and T. aequipes*, which were only found on this wall (British Arachnology Society 2013). This antagonism between the different spider species found on living walls, i.e. favouring low vs. high vegetation, natural vs. built habitats, damp vs. dry conditions, shows the ubiquity and the variety of resources that may be provided by vertical greening systems.

6.7.3.2 Effect of the different systems and the characteristics of the living walls on spider population

Spider fauna, with the exception of the orb-weaving group, was more abundant and diverse on living walls than on green screens. As web-spiders have been shown to be positively related to plant structural diversity (Uetz 1991), this difference may be due to the greater plant richness of the LW systems compared to the green screens.

Between the different living wall systems, some differences were obvious: angled plastic modules and rockwool units attracted a more abundant and diverse spider fauna than horizontal plant boxes and plant pots. However, there were relatively few study sites with horizontal plant box or plant pot systems, and it is possible that the validity of the findings could be questioned despite the significance of the results.

Most of the living walls were installed with fully-grown plants. However, the age of the walls, ranging from 1 year and 3 months old to 4 years and 2 months old at the time of the study (dated in July 2012), has been shown in this study to be positively related to spider abundance and richness. As such, it appears that the age of the wall seems to be as important as the plants establishment and growth. This could further explain why spider abundance was lower in the horizontal plant boxes and plant pots walls as these walls were among the youngest sites. The influence of the age of the living wall on spider abundance and richness is probably a result of the species succession that happens in each animal community over time (Varet *et al.* 2013). Furthermore, spider's preys, i.e. other invertebrates such as insects, may become gradually more abundant over time, attracting more spiders on site.

The positive relationship between plant density/richness and spider abundance/richness may be explained by the specific web attachment requirements of web-buildings spiders (contributing to 90.6% of total abundance - Uetz 1991). Moreover, vegetation richness and density have been shown to influence spider abundance and richness by changing foraging efficiency and/or the nutritional quality of the herbivore prey (see Rypstra *et al.* 1999 and references therein; Diehl *et al.* 2013). This may explain the greater spider abundance in the angled plastic module walls, as this system had the greatest plant density of those studied.

6.7.3.3 Effect of the surrounding environment on spider population

Vehicle traffic volume was negatively related to spider abundance using visual searching (sampling the outer surface of the foliage), whilst it was not related to spider abundance or spider richness using suction (sampling the outer surface and within the foliage). The minimum distance between the road and a living wall site was 4 meters. Although spiders were avoiding the outer surface perhaps because of air turbulences, this distance might be enough for vehicle effects to be minimal on animals within the foliage, and as such create an isolated habitat where spiders can settle.

Pedestrian traffic was negatively related to spider fauna. This may be related to the disturbance caused by pedestrians walking past either without physical contact with the vegetation or deliberately touching it. In public areas where living walls were in direct contact with many city-dwellers, spider abundance and richness were lower than in private areas where peoples' interactions with the wall were less frequent. Moreover, in public areas where pedestrians are not just passing by but are also spending time (e.g. a shopping centre or a park as opposed to a walking street), maintenance interventions were likely to be more frequent and intense to keep the wall at its peak aesthetic quality (i.e. trimming, removal of dead leaves, dead flowers, dead plants, weeds, etc.). Therefore, it is likely that both frequency of human disturbance and intensity of interventions have a negative effect on spider fauna. No evidence of a direct influence of human disturbance on spider could be found in the literature. However, work from previous studies suggests that this negative relationship may be related to the human disturbance on insect fauna (Mathew & Rugmini 2005; Ye *et al.* 2012; Schowalter 2012) resulting indirectly in a less abundant spider population. Sheet- and tangle-weavers were negatively affected by pedestrian traffic volume, whilst no relationship was found between pedestrian levels and orb-weavers. As such, there were on living walls in public areas proportionally more orb-weavers, and less sheet- and tangle-weavers, than in private areas.

Surrounding vegetation did not affect the use of the living walls by spiders. This may be because of a range of factors but may suggest that spider find the protection and extent of the resources they need within the green walls, and that the major factor affecting spider use of GW may be anthropogenic.

6.7.4 Colonisation of new living walls by spiders

The monitoring of the new living wall at Staffordshire University gave useful information on the first species that colonise a newly planted GW in the urban environment. *Araneus diadementus*, *Z. X-notata* and *T. tenuis*, generalist species that are regarded as ubiquitous, were expected in this context as pioneer species (Milner 2000). Despite the north-facing aspect of the wall and the windy conditions, spiders were able to use this new habitat and were slowly colonising it as shown by the increasing abundance over the weeks.

Structural diversity was greater in the non-flowering blocks, where the three plants species were spread evenly, than in the flowering blocks where *Heuchera sp.* covered most of the surface (see section 3.1.3 for botanical composition). As web-spiders favour high structural diversity (Uetz 1991), this difference may be related to the greater spider abundance found in the non-flowering treatment than in the flowering treatment, when data from both heights were aggregated and in each height.

The higher blocks were less accessible for visual searching than the lower blocks, which might have resulted in a bias; however, the equivalent abundances between the two heights of each vegetation composition suggest this is unlikely. The wall was set up in a windy area (the fieldwork was often postponed due to wind speed greater than level 3 on the Beaufort scale, see section 3.2 for further details on methodology), and it is likely that the turbulences were stronger higher up, with a threshold around 1.5 m high (Hang *et al.* 2013). As such, wind may be one of the reasons for the greater abundance in the lower blocks (between 0.2 m and 1.4 m high) than in the higher blocks (between 1.4 m and 2.6 m high).

6.7.5 Comparison between green façades, living walls and green screens

Statistical analysis between the spider fauna of green façades and living walls could not be carried out as surveys were made in different years and study sites differed in many ways. Most of the green façades studied were mainly in private and/or relatively quiet environments (88% of the total), plus were trimmed on average twice a year, whereas the living walls were mainly in busy and public areas (91% of the total), maintained on average every fortnight (for further details on GF and LW, please see section 3.1). Despite these differences, the total species richness of spiders was similar on GF and LW (19 and 22 species respectively), as was the mean species richness found by wall (7.6 ±0.64 and 7.7 ±0.5 respectively). However, comparison of species compositions reveals that only eight family (57.1%) and seven genera (23.3%) have been found in both systems (see Table 6.15 for further details). Ten genera were exclusively found on green façades, ten others were exclusively found on living walls. These differences suggest a discreet complementarity between GF and LW, probably related to their environmental and structural composition.

Plant richness affected spider populations on living walls but not on green façades. This may be due to the far greater diversity of plants on living walls (minimum five different genera and fourteen different genera on average); whereas green façades were typically monoculture with the most diverse walls only composed of six genera maximum.

Green screens and most of the green façades studied were made of *Hedera spp*. (see Table 3.1); however, spider abundance and species richness in green façades was far greater than the abundance and richness on green screens. The differences may be related to the density of plant cover and to the shelter provided by the wall. On green screens, the depth of the vegetation was kept to a minimum (few centimetres away from the wire mesh) to keep the fence-like character; whilst on green façades vegetation was quite dense and deep with many layers of leaves and usually a dense 'woody structure' behind the leaves (Metcalfe 2005). It was usually possible to see 'through' the green screens studied, whereas vegetation on façades hid the building surface.

Suction sampling is more efficient than visual searching on green façades and living walls, whereas visual searching is more efficient on a new living wall. This may be because the less abundant vegetation on new walls makes the visual searching easier.

In this study, no relationship was found between the vegetation surface area of the walls (both GF and LW) and spider abundance or richness. As most walls were higher than they were wide, this may be related to the vertical sampling area being restricted to the section between the ground and a height of 2 metres. As such, it is possible to suspect a gradient of abundance on the vertical dimension, although no evidence of a potential influence of the height on spider population was found in the published literature.

Wall aspect had no effect on spider abundance and richness. There are obvious abiotic factors related to aspect (insolation, wind, solar exposure etc., see Gardiner & Dover 2007) which are likely to create more favourable conditions in some aspects than others. However, no relationships was found with the data and this is perhaps because the vegetation and the physical structure of the wall (either GF or LW) created a microclimate (Sternberg *et al.* 2011) sufficient for spiders and their prey to settle on any aspect. No previous studies on the effect of the aspects of hedgerows, building façades and vertical structures were found on this subject to facilitate further discussion

6.7.6 Spider population of green walls compared to other ecosystems

In Hungary, Samu *et al.* (2002) found nine different species on bare buildings, a similar species richness to that found on bare walls in this study in England. Only the species *A. diadementus* and *S. bipunctata* were found in both studies, perhaps due to the different geographic locations. The only previously published work found on spider communities of urban green façades is that of Köhler *et al.* (1993) in Germany; none were found published in English. In Berlin, Köhler *et al.* (1993) found eight dominant spider genera on green façades made of vine or ivy plants, mainly *Tegenaria domestica* (32%), *Harpactea sp.* (22%) and *Theridion sp.* (18%). In this study, spider fauna on green façades resulted in a wider range of species were found; although as with Köhler *et al.* (1993), three species also dominated the samples (*A. similis* (24.1%), *A. diadementus* (16.2%) and *Z. x-notata* (10.6%)).

No other studies on the spider fauna of living walls or green screens have been reported in the literature, and no direct comparison between the data presented here and other studies are possible. Furthermore, direct comparison between green walls and other structures is not feasible due to variations between length of study, sampling area, and sampling methods. For example in London, spider records are mainly done in green spaces such as Hampstead Heath, the Regent's and Hyde Parks (Milner 1993, 1999, 2000, 2005). Because of their obvious differences in area and habitat heterogeneity, it is not possible to compare their spider diversity with the one found on LW. Spider species richness seems to be greater on urban green walls than on urban green roofs, seeded either with native or non-native wildflower mixes (Kadas 2011). However, spider communities appear to be less rich on green walls than on green roofs with diverse substrates and plant species (Brenneisen & Haenggi 2006; Kadas 2011; Madre *et al.* 2013). This difference may be related to the "piggy-back" arrival of spider species on the roofs within the growing media and plants. Compared to brownfield sites, species richness on urban green walls appears to be less rich, although spider diversity on brownfield sites was shown to be highly dependent on the site itself and the year (Kadas 2011). The species richness of spiders seems to be similar on urban walls and on rural hedgerows, either placed adjacent to a forest or completely isolated (roughly ten and six species respectively according to Fischer *et al.* (2013)), although when of great biological quality, hedges are likely to show a greater species richness (up to 14.3 ±2.7 in Ysnel & Canard (2000)).

Urban areas are dynamic environments in which wildlife can be marginalised. As human activities alter the relative abundance and composition of species (Faeth *et al.* 2005), cities harbour different species assemblages compared to agricultural or forest areas (Sattler *et al.* 2011). Spiders are generalist predators of their food web (Greenstone 1999), occupying the mid-trophic level of the food chain (Harwood *et al.* 2001). As such their abundance and richness can be directly linked with a diverse invertebrate fauna. The distinct abundance and richness of spiders on green façades and living walls highlights the role of this ecosystem as urban habitat for invertebrates as it provides new and distinct opportunities for a wide range of species. The introduction of such green elements has an important role to play in improving the ecological functionality of our cities.

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CHAPTER VII

THE VALUE OF GREEN WALLS FOR URBAN INSECT POPULATIONS

7. THE VALUE OF GREEN WALLS FOR URBAN INSECT POPULATIONS

This chapter presents the results from an investigation into the value of green façades and living walls to insect populations.

7.1 ABSTRACT

The value of urban green walls for insect biodiversity was investigated in Stoke-on-Trent, Birmingham, London, and The Great London Area, UK, using 29 green façades, walls covered with climbing plants or/and wall shrubs, and 22 living walls, plants rooted in panels attached to the wall with a built-in irrigation system. Insects were sampled using a suction sampling device in the summer and autumn of 2011 for the GF and in the summer of 2012 for the LW. Their value was investigated by comparing them to 29 bare walls and 4 green screens (free-standing, ivy-covered mesh), focusing on the overall insect abundance and species richness, and also more specifically on the abundance and species richness of the Coleoptera, Diptera, Hemiptera and Hymenoptera orders. Direct factors such as the characteristics of the green walls (e.g. vegetation surface area, aspect, plant species richness and density, type of foliage, type of living wall system) and indirect factors (e.g. surrounding vegetation, vehicle traffic and pedestrian traffic volumes, seasonality) were studied.

Overall, 6404 insects were sampled on the green façades, belonging to 11 orders, 86 families and 208 species or morphospecies and on living walls, 1399 insects, belonging to 9 orders, 61 families and 137 species or morphospecies. On green screens, 360 specimens belonging to 6 orders, 37 families, 55 species or morphospecies were sampled. Insect fauna as a whole showed little variation in abundance and richness, however, individual insect orders showed significant variations, wherein certain orders are more affected by some of the factors than others. As such, Coleoptera population was influenced by the green wall vegetation surface area, the type of foliage, the height of the wall, the nearby surrounding vegetation and the vehicle traffic volume. Diptera population was affected by the vegetation composition, richness and density, the type of foliage, the height of the wall, the age of the wall, the type of living wall system, and the seasonality. Hemiptera population was affected by the vegetation surface area, the vegetation composition, the type of foliage, the height of the wall, the type of living wall system, the nearby surrounding vegetation and the seasonality. Hymenoptera population was influenced by the height of the wall and the pedestrian traffic volumes.

The findings of the study are two-fold, (i) local environment has an effect on insect populations of green walls, (ii) the characteristics of green façades and living walls influence the species groups found on them and as such, hold the potential for the design of planting schemes to favour particular target groups.

7.2 INTRODUCTION

The total abundance and species richness of insects on green walls (GW) was investigated with a specific focus on the following orders more specifically: Coleoptera, Diptera, Hemiptera and Hymenoptera. These orders are of special interest as they are important food sources for several vertebrate species (Kervyn & Libois 2008; Helden *et al.* 2012), are often used as bioindicators (Varet *et al.* 2011; Carew *et al.* 2013), and many are important pollinators (Griffin *et al.* 2009; Pélabon *et al.* 2012; Bashir *et al.* 2013). Previous studies showed the value of ivy *Hedera spp.* found either on walls, trees or as ground-cover plants, for insects (Diefenbach & Becker 1992; Metcalfe 2005; Jacobs *et al.* 2009; Garbuzov & Ratnieks 2014). Insects foraging on ivy are mostly of the Hymenoptera and Diptera orders (Metcalfe 2005; Jacobs *et al.* 2009) and are especially active during the day (Jacobs *et al.* 2010).

Amongst direct factors, insect populations on green walls may be influenced by the surface area of vegetation (Hannunen 2002), the plant structural and botanical composition (e.g. abundance of flowers) (Maudsley 2000; Strauss & Biedermann 2006), the plant richness (Wei *et al.* 2010), the foliage, i.e. evergreen vs. deciduous (Basset 1994), and the type of green wall system. Similarly, indirect factors such as seasonality (Sugiura 2012), surrounding vegetation (Köhler *et al.* 1993; Emery *et al.* 2004; Matteson *et al.* 2013), and pedestrian and vehicle traffic volumes (Adams & Lindsey 2009) may have varying effects.

The aim of the study was to assess the value for insect biodiversity of (i) green façades (GF, i.e. walls covered with climbing plants or wall shrubs) and (ii) living walls (LW, i.e. artificial structure made of continuous or modular units, with plants rooted into, attached to the wall with a built-in irrigation system) with a focus on their characteristics and their surrounding environment. Using a suction sampling device, insect populations of well-established green façades and living walls were monitored in several locations of England, UK. In addition, a new living wall was set up specifically for this study on the Staffordshire University campus of Stoke-on-Trent, UK.

The study of green façades was designed to test the following hypotheses about their value as an insect habitat:

1. Green façades are expected to have greater insect abundance and species richness than equivalent unvegetated walls.
2. Total insect abundance, total species richness, and abundances and richnesses of the Coleoptera, Diptera, Hemiptera and Hymenoptera orders will be affected by the season of sampling.
3. Green façades with evergreen foliage are expected to show greater insect abundance and species richness, in total and by order, than green façades with deciduous foliage especially in the autumn. Differences are also expected for green façades made of diverse

plant species compared to green façades with single plant species (with a distinction between GF with *Hedera sp.* (ivy) and other plants).

4. Vegetation surface area is expected to be positively related to insect abundance and species richness (in total and by order).
5. South-facing walls are expected to have greater insect abundance and species richness than north-facing walls.

The study of established living walls was designed to test the following hypotheses about their value as an insect habitat:

1. Different living wall systems (LWS, e.g. rockwool units, plastic modules) are expected to differ in total insect abundance and richness, and specifically in abundance and richness of the Coleoptera, Diptera, Hemiptera and Hymenoptera orders.
2. Characteristics of the wall, i.e. age of the wall, vegetation surface area, plant density and plant richness, are expected to be positively related to insect abundance and richness, in total and by order.
3. South-facing walls are expected to have greater insect abundance and species richness than north-facing walls.
4. The environment of the wall, i.e. presence and abundance of surrounding vegetation, vehicle traffic and the pedestrian densities are expected to affect insect populations of the LW (the abundance of surrounding vegetation positively and the vehicle and pedestrian traffic volumes negatively).

The study of a new living wall was designed to test the following hypotheses about their value as an insect habitat:

1. Insect populations will be similar between the edges of the living wall and its centre.
2. Insect populations will be greater in flowering treatment than in non-flowering treatment.
3. Insect populations will be affected by sampling height.
4. Colonisation rate of insects will increase over time in density and richness.

7.3 MATERIAL AND METHODS

7.3.1 Study Sites

For detailed information on study sites, please refer to section 3.1.1 for the green façades, to section 3.1.2 for the established living walls, and to section 3.1.3 for the new living wall.

7.3.2 Insect surveys

For detailed information on insect surveys, please refer to section 3.2. Following preservation in 70% ethanol, specimens were counted and, where possible, identified to family level (Table 7.1), and to species or morphospecies levels following the technique of Oliver & Beattie (1996). Specimens only identifiable to order level, either due to damage or developmental stage, were given the order name followed by 'UI' for 'unidentifiable individuals'; they were included in abundance analysis but discarded from species richness analysis. This conservative approach avoided inflating species richness measures (Morrison *et al.* 2012).

7.3.3 Data Analysis

The variables studied were: total insect abundance and richness (of all the orders found), abundance and richness of the orders Coleoptera, Diptera, Hemiptera and Hymenoptera.

On green façades, the factors investigated were the impact of: vegetation on walls (n=29) compared to the paired control (bare walls, n=29), seasonality (summer vs. autumn), type of foliage (evergreen (n=23) vs. deciduous (n=6)), the vegetation diversity (whether the green wall consisted of a single plant species (n=19) or many species (n=10), and with a distinction between walls with or without *Hedera sp*.(see Table 3.1)), the surface area of the vegetation, and the aspect (categorised on the basis of the four cardinal directions and the four intercardinal directions). For detailed information on the GF characteristics, please see Table 3.1.

On the established living walls, the factors investigated were: (i) the differences between cities (Birmingham vs. London), (ii) the changes in abundance and richness over time (four samples were taken with fortnightly intervals), (iii) the effect of different green wall systems (6 different living wall systems, see section 3.1.2) and green screens, (iv) the plant density (per m²) and the plant richness effects (counting the different genera and not the different cultivar, see Appendix 5), (v) the vegetation surface area, (vi) the aspect, (vii) the LW age effect and (viii) the pedestrian and vehicle traffic volumes. For detailed information on the LW characteristics, please refer to Table 3.2.

On the new living wall, the factors investigated were: the height (low vs. high), the vegetation composition categories (flowering vs. non-flowering) and changes in abundance and richness over time (five samples taken with fortnightly intervals).

For detail of the statistical tests, please refer to section 3.3. Comparative analyses were carried out on the mean abundances and richnesses found on wall for each visit (with three samples in the summer 2011 and three samples in the autumn 2011 on GF, and four samples in the summer 2012 for LW).

Multiple Correspondence Analysis

Ordination using multiple correspondence analysis (MCA) was applied to the living wall-insect dataset (Greenacre 1983; Ludwig & Reynolds 1988; Legendre & Legendre 1998), first to data for all sites (n= 26) and subsequently excluding data for sites with green screens (n= 22). MCA is a constrained ordination and allows the relationship of two sets of variables to be explored; in this case taxa against potential factors. Much like factor analysis it provides for the collapse of variation into a small subset of variables. However, it is based on Pearson's Chi-square; the method decomposes the overall Chi-square statistic (or Inertia, i.e. Chi-square/Total N, where N are total frequencies in the table) by identifying a small number of dimensions in which the deviations from the expected values can be represented. The percentage variation explained by a single dimension (axis) is the relative amount of the overall Chi-square value that be reconstructed from that dimension.

Usually two or three dimensions are explored, depending on the eigenvalues. In the current analysis, taxonomic variables were made current and the factors entered as supplementary to the analysis. This provided exploration of the structure of the two sets of variables in two dimensions accounting for >50% variation in taxa variables (their diversity and abundance).

First, means were obtained for sites across sample events, so that the Burt table for MCA comprised sites (rows) and variables (taxa; factors). The variables were then transformed to provide categories, typically binary classes providing ranks in effect, thus ensuring minimum dimensions for the Burt table and minimising cells in the matrix with zero or low value entries (<5). Categories for both location and system were left unchanged, Birmingham, London and Stoke-on-Trent were coded Loc B, L and S respectively, and the different systems angled plastic module, horizontal plant box, plastic pot, rockwool and green screens were coded sys APM, BP, PP, R and GS respectively). Most continuous variables, i.e. walls' characteristics (age, plant diversity, plant density, total vegetation surface and taxa abundance and diversity, were divided about the median with lower and upper halves coded 1 and 2 respectively. Wall aspects were distinguished into north and south divided by a west-east line (south of west and north of west). Both surrounding vegetation and vehicle traffic were divided into two groups with arrow's extremity 1 and 2 representing categories 0/1 and 2/3 respectively; coding for pedestrian traffic was also contracted into two groups with arrow's extremity 1 and 2 representing categories 1 and 2/3 respectively (see section 3.1.2 and Table 3.1).

7.4 RESULTS –VALUE OF GREEN FAÇADES FOR INSECTS

7.4.1 Insect populations in green façades compared to bare walls

Overall, 6404 insects were found on the 29 green façades: 86 families and 208 species or morphospecies were identified from eleven orders (Table 7.2). The most family-rich orders were Diptera (38 families), Hymenoptera (18 families) and Hemiptera (13 families). The most species-rich families were Pteromalidae (15 species), Braconidae (8 species), Eulophidae (8 species), Carabidae (6 species) and Pentatomidae (6 species). When samples from the summer and the autumn are combined, 32.0 ±1.78 species were found on average on green façades, of which 2.8 ±0.3 Coleopteran species, 11 ±0.84 Dipteran species, 6.5 ±0.5 Hemipteran species and 8.3 ±0.75 Hymenoptera species.

The families with the greatest abundance were Ectopsocidae (1135 individuals), Pteromalidae (526 individuals), Cidadellidae (415 individuals), Aphididae (390 individuals), Cecidomyiidae (383 individuals) and Figitidae (316 individuals). Eleven families (12.8%) were singletons and seventeen families (19.8%) were represented by fewer than five individuals. Twenty-five species (12.0%) were singletons and sixty-five species (31.2%) were represented by fewer than five individuals. Due to damage or developmental stage, 121 insects (1.89%) could only be identified to order or super-family levels and were only included in abundance analysis (total and by order). A further 26 specimens (0.4%) could not be identified to order level and were only included in analysis of total abundance. In addition to these insects, 4 Myriapoda, 99 Malacostra (Isopoda) and 791 Collembola were captured; these were not included in the analysis of abundance and richness (Table 7.2).

Only 158 Collembola and 124 insects: 97 Psocoptera, 5 Chalcidoidae (Hymenoptera - one species) and 2 Ephrydidae (Diptera - one species) were found on the 29 bare walls. Insect abundance on green façades (36.8 ±2.40 specimen were found on a wall on one occasion) was greater than on their paired bare walls (0.1 ±0.00) ($z=-5.90$, $n=29$, $p<0.001$), as was species richness ($z=-5.78$, $n=29$, $p<0.001$). The following analyses refer to differences between green façades attributes only, to establish if different characteristics (such as seasonality or the type of foliage) had any impact on insect abundance and species richness (in total and by order).

7.4.2 Seasonality effect on insect populations

Total insect abundance was similar in the summer (35.8 ±3.62) and in the autumn (37.8 ±3.17) ($p=0.754$). Total species richness was similar in the summer (4.9 ±0.57) and in the autumn (5.8 ±0.44 species) ($p=0.193$).

Overall, Coleoptera were significantly less abundant and species rich than Diptera, Hemiptera and Hymenoptera (see Fig. 7.1, Table 7.3 for statistical results). Abundances of Diptera, Hemiptera and Hymenoptera were similar (Fig. 7.1a); whilst Diptera were more species rich than Hemiptera and Hymenoptera (Fig. 7.1b, Table 7.3). Seasonality did not affect the abundances of Coleoptera, Diptera, Hemiptera and Hymenoptera (Fig. 7.2a, Table 7.4). Seasonality had also no effect on the species richness of Coleoptera and Hymenoptera (Table 7.4), whereas Diptera were more species rich in the autumn and Hemiptera were more species rich in the summer (Fig. 7.2b, Table 7.4). Coleoptera were less abundant than the other orders in each season (Fig. 7.2a, Table 7.4). Dipteran abundance was similar to the abundances of Hemiptera and Hymenoptera in the summer but was significantly greater in the autumn, whilst abundances of Hemiptera and Hymenoptera were similar in each season (Fig. 7.2a, Table 7.4). Coleoptera were less species rich than the other orders in each season (Fig. 7.2b, Table 7.4). Species richness of Diptera, Hemiptera and Hymenoptera were similar in the summer, whilst Diptera was more species rich in the autumn than Hemiptera and Hymenoptera (Fig. 7.2b, Table 7.4).

7.4.3 Effect of foliage type on capture rates and on seasonality

Walls were covered with either deciduous or evergreen foliage (6 and 23 sites respectively) and, overall, insects were more abundant in evergreen foliage than in deciduous foliage (40.5 ±2.78 and 19.0 ±1.82 individuals respectively, $z=-4.33$, $n_1=23$, $n_2=6$, $p<0.001$). The total insect species richness was also greater in evergreen foliage than in deciduous foliage (11.8 ±0.43 and 7.9 ±0.49 species respectively, $z=-4.17$, $n_1=23$, $n_2=6$, $p<0.001$). In both summer and autumn, insects were more abundant and diverse in evergreen foliage than in deciduous foliage (see Fig. 7.3 and Table 7.5 for further details). In each type of foliage, seasonality had no effect on total insect abundance and richness (Fig. 7.3, Table 7.5).

Overall, abundance and species richness of insect orders were affected differently by the type of foliage (Fig. 7.4). There was no effect of the type of foliage on abundances and species richness of Hemiptera and Hymenoptera, whilst Coleoptera were more abundant and Diptera were more abundant and species rich in evergreen foliage than in deciduous foliage (Fig. 7.4, Table 7.6). Coleoptera were less abundant and species rich than the other orders in both types of foliage, whilst Diptera was the most abundant and rich order in evergreen foliage (although not significantly than Hymenoptera in evergreen foliage, see Table 7.6).

The season of sampling affected the abundance and richness of insect orders differently depending on the type of foliage (Fig. 7.5).

Coleoptera were more abundant in evergreen foliage than in deciduous foliage in the autumn but showed similar abundances between the two foliages in the summer. There were more Coleoptera in evergreen foliage in the autumn than in the summer, however the season of sampling had no effect on the abundance in deciduous foliage (Fig. 7.5a, Table 7.7). Coleoptera richness was not affected by the type of foliage in each season, or by the season of sampling in deciduous foliage or in evergreen foliage (Fig. 7.5b, Table 7.7).

Dipteran abundance and richness were greater in evergreen foliage than in deciduous foliage in the summer and in the autumn. Dipteran abundance was similar between season in both types of foliage, whilst species richness was significantly greater on evergreen foliage in the autumn than in the summer (Fig. 7.5, Table 7.7).

Abundance and richness of Hemiptera and Hymenoptera were not affected by the type of foliage in each season, nor by the season of sampling in both foliages (Fig. 7.5, Table 7.7).

During both seasons, Coleoptera were less abundant and species rich than the other orders for both types of foliage, whereas Diptera were more abundant and rich than the other orders in evergreen foliage in the summer and in the autumn (although not always significantly, see Table 7.7).

7.4.4 Effect of the plant diversity on insect populations

A distinction was made between green façades consisting of a single plant species (19 sites) or of multiple species (10 sites). Total insect abundance was similar on single-species walls (36.1 ±2.23) and on diverse species walls (38.2 ±5.54), when data from both seasons were aggregated (*p*=0.125), and in each season ($H_{(3)}$= 3.88, *p*=0.275). Species richness was similar on single-species walls (11.1 ±0.38 species) and on diverse species walls (11.1 ±0.84), when data from both seasons were aggregated (*p*=0.234), and in each season ($H_{(3)}$= 3.14, *p*=0.370).

A distinction was made between green façades exclusively made of *Hedera sp.*, either as a single species (a '*Hedera* monoculture', n=15) or with multiple species (a '*Hedera* polyculture', n=5), and walls made of other plants, either as a monoculture (n=4) or a polyculture (sometimes with one or two *Hedera sp.* in the plant composition, n=5) (see Table 3.1 for details of GF botanical composition). When these four groups were considered, there were significant differences between insect abundances and species richness, in total ($H_{(3)}$= 10.65, *p*=0.014 and $H_{(3)}$= 11.81, *p*=0.008 respectively) and in each season (Fig. 7.6, Table 7.8). When data from both seasons were aggregated, the total abundance and species richness of insects on GF with a *Hedera* 'polyculture' were greater than on GF with a polyculture composed of other species, (z=-2.07, *p*=0.038; z=-2.51, *p*=0.012 respectively). This was also the case for each individual season, although not significantly in the summer (Fig. 7.6 and Table 7.8). However, there were no differences in abundances and richness (i) between GF with *Hedera sp.* either as a monoculture or a polyculture, (ii) between GF with a polyculture or a monoculture other than *Hedera spp.*, and (iii) between GF with a single *Hedera sp.* and GF with another single species (Fig. 7.6, Table 7.8).

Abundance and species richness of the different orders were affected differently whether the vegetation was composed of a monoculture or a polyculture, both when data from both seasons were aggregated and in each individual season (Fig. 7.7, 7.8).

Dipteran abundance was not affected by vegetation diversity (monoculture vs. polyculture) either in total (*p*=0.357) or in each season (Fig. 7.7a, Table 7.9). Dipteran species richness was not affected by vegetation diversity in total (*p*=0.099) but was greater in GF with a monoculture in the autumn than in the summer (Fig. 7.7b, Table 7.9). In the summer, the distinction between walls with or without *Hedera sp.* did not affect abundance or species richness (Fig. 7.8, Table 7.10). However, in the autumn, abundance was greater in (i) GF with a '*Hedera* polyculture' than GF with a polyculture of other species, and in (ii) GF with a single *Hedera sp.* than a single other species (Fig. 7.8a, Table 7.10). Furthermore, species richness was greater in GF with a '*Hedera* polyculture' than GF with a polyculture of other species in the autumn (Fig. 7.8b, Table 7.10).

Hemipteran abundance and species richness were not affected by the vegetation diversity of the GF either in total (*p*=0.814 and *p*=0.859 respectively) or in each season (Fig. 7.7, Table 7.9). The distinction between walls with or without *Hedera* did not affect the abundance in total (*p*=0.753) or in each season (Table 7.10). However, in the autumn, Hemipteran richness in GF with a '*Hedera* polyculture' was greater than in GF with a polyculture composed of other species and in GF with a single *Hedera sp.*, in total (z=-3.00, n=5, *p*=0.003 and z=-2.83, n_1=5, n_2=15, *p*=0.005 respectively), and in the autumn; this was not the case in the summer (Fig. 7.8, Table 7.10).

Abundance and species richness of Coleoptera and Hymenoptera were not affected by the vegetation diversity (monoculture vs. polyculture) of the GF or by the presence/absence of *Hedera sp.* on the wall, in total (*p*>0.05) and in each season (see Fig. 7.7, 7.8 and Tables 7.9, 7.10).

7.4.5 Effects of green façades size and aspect on insect populations

The green façades varied in vegetation surface area and in aspect (see Table 3.1).

Vegetation surface area was not related to the total abundance and species richness of insect (*p*>0.05), nor was it with the abundance and species richness of Coleoptera, Diptera, Hemiptera and Hymenoptera (*p*>0.05).

The aspect of the wall, categorised either on the basis of the four cardinal directions or on the basis of the four cardinal plus the four intercardinal directions, had no effect on insect abundance and richness, either total or by order (*p*>0.05).

7.5 RESULTS – VALUE OF ESTABLISHED LIVING WALLS FOR INSECTS

7.5.1 Insect populations on established living walls

Overall, in Birmingham and London, 1399 insects were found on the living walls: 61 families and 137 species were identified from nine orders (Table 7.11). The most family-rich orders were Diptera (23 families) and Hymenoptera (14 families). The most species-rich families were Braconidae (8 species), Chironomidae (8 species), Sciaridae (8 species), and Lathridiidae (6 species). On average, 20.4 ±1.13 species were found on living walls, of which 1.9 ±0.3 Coleopteran species, 8.6 ±0.79 Dipteran species, 3.0 ±0.30 Hemipteran species and 5.0 ±0.67 Hymenopteran species.

The families with the greatest abundance were Aphididae (308 individuals), Psychodidae (134 individuals), Sciaridae (125 individuals) and Chironomidae (108 individuals). Fourteen families (22.9%) were singletons and twenty-seven families (44.3%) were represented by fewer than five individuals. Thirty-seven species (27.0%) were singletons and eighty-two species (59.8%) were represented by fewer than five individuals. Due to damage or developmental stage, 17 individuals (0.01%) could only be identified to the order or super-family levels and were only included in the analysis of abundance (total and by order). In addition to these insects, 8 Malacostra (Isopoda) and 183 Collembola were captured; these were not included in the analysis of abundance and richness (Table 7.11).

On green screens (GS), 360 specimens were sampled, belonging to 59 species, 37 families and 6 orders (Table 7.12). The most family-rich orders were Diptera (17 families), Hymenoptera (8 families) and Hemiptera (6 families). The most species-rich families were Chironomidae (6 species), Sciaridae (4 species), and Braconidae (3 species). On average, 24.2 ±1.67 species were found on average on green screens (of which 0.5 ±0.43 Coleopteran species, 12.7 ±1.88 Dipteran species, 2.2 ±0.74 Hemipteran species and 6.2 ±0.41 Hymenopteran species).

The families with the greatest abundance were Pteromalidae (105 individuals), Aphididae (86 individuals), and Chironomidae (50 individuals). On green screens, all specimens were identifiable past the order level. Fifteen families (40.5%) were singletons and twenty-six families (70.3%) were represented by fewer than five individuals. Twenty-eight species (47.4%) were singletons and forty-six species (78.0%) were represented by fewer than five individuals.

7.5.2 Effect of the LW system on insect populations

Only one type of LWS, the angled plastic module, was present in both London and Birmingham. The analysis of this system across 13 walls (8 in Birmingham and 5 in London) showed no differences in abundance or in species richness between the two cities (p=0.336 and p=0.201 respectively). Following these results, data were aggregated for the two cities.

There were no differences in total insect abundance and species richness between the six different LWS and the green screens (Fig. 7.9); however, the type of LW had an effect on the abundance and species richness of some of the insect orders (Fig. 7.10).

The abundance and richness of Diptera were affected by the six types of system (Fig. 7.10, Table 7.13). The three different rockwool systems were aggregated as there were no significant differences between them in Dipteran abundance and richness (p=0.358, p=0.485 respectively), as were the green screens in London and Stoke-on-Trent (p=0.442, p=0.328 respectively). Dipteran abundance was significantly greater in horizontal plant boxes than on all the other systems (with the exception of plant pot systems) and was significantly greater in plant pot systems than in angled plastic modules (Fig. 7.10a). Dipteran richness was significantly greater in horizontal plant boxes, plant pots and green screens than in angled plastic modules (Fig. 7.10b). There were no differences in Dipteran abundance and richness between green screens, plant pots and rockwool units (Fig. 7.10, Table 7.13).

Hemipteran abundance and richness were affected by the six types of system (Fig. 7.10, Table 7.13). The three different rockwool systems were aggregated as there were no significant differences between them in Hemipteran abundance and richness (p=0.483, p=0.146 respectively); as were the green screens in London and Stoke-on-Trent (p=0.195, p=0.442 respectively). Hemipteran abundance was significantly greater in rockwool units than in all the other systems (with the exception of green screens) and was significantly greater in angled plastic modules than in plant pots and horizontal plant boxes (Fig. 7.10a). Hemipteran richness was greater in rockwool units than in all the other systems (Fig. 7.10b) and was significantly greater in angled plastic modules than in plant pots. There were no differences in abundance and richness between green screens, plant pots and horizontal plant boxes.

Coleopteran and Hymenopteran abundance and richness were not affected by the type of system (Fig. 7.10, Table 7.13).

7.5.3 Time effect on insect abundance and species richness on LW

The period of sampling affected insect populations in London and Birmingham differently (Fig. 7.11, Table 7.14). In Birmingham, total insect abundance and species richness increased continuously with a significant difference between the first three samples and the 4th sample (Fig. 7.11a,c, Table 7.14). In London, the abundance and species richness showed a sawtooth-like change over time but with no significant differences (Fig. 7.11b,d and Table 7.14).

In Birmingham, the period of sampling had no effect on the abundance and species richness of the different orders (Fig. 7.12a,c, Table 7.15). In London, the period of sampling had no effect on the abundances of Coleoptera, Hemiptera and Hymenoptera, whilst the abundance of Diptera increased significantly between the 1st sample and the 3rd and 4th ones (Fig. 7.12b, Table 7.15). The period of sampling had no effect on the species richness of the different orders in London (Fig. 7.12d, Table 7.15).

7.5.4 Effect of LW characteristics on insect populations

The living walls varied in age, in vegetation surface area, in plant density and richness and in aspect (see Table 3.2 and Appendix 5). These different characteristics did not significantly affect the total insect abundance and species richness (p>0.05) but did show a significant relationship with the abundance and richness of the different orders.

There was a negative, and significant, relationship between the age of the LW and Dipteran species richness (R^2=0.25, $F_{1,21}$=7.95, p=0.009 - Fig. 7.13b) and whilst the trend was similar for Dipteran abundance (Fig. 7.13a), it failed to achieve significance (p=0.098). The abundance or species richness of the other orders were not related to the age of the LW (p>0.05).

The surface area of wall vegetation was not significantly related to Coleopteran abundance (p=0.204 - Fig. 7.13c) but was significantly positively related to Coleopteran richness (R^2=0.16, $F_{1,21}$=4.49, p=0.045 - Fig. 7.13d) and Hemipteran abundance and species richness (R^2=0.31, $F_{1,21}$=8.96, p=0.007 and R^2=0.30, $F_{1,21}$=8.44, p=0.009 respectively - Fig. 7.13e,f). No relationship was found between vegetation area and the abundance and species richness of Diptera and Hymenoptera (p>0.05).

The LW plant density was significantly negatively related to Dipteran abundance and richness (R^2=0.20, $F_{1,21}$=4.93, p=0.038; R^2=0.28, $F_{1,21}$=7.83, p=0.011 respectively - Fig. 7.13g,h), however, no relationship was found with the other orders (p>0.05).

There was a negative and significant relationship between the LW plant richness and Dipteran abundance and richness (R^2=0.28, $F_{1,21}$=7.90, p=0.011; R^2=0.38, $F_{1,21}$=14.814, p=0.001 respectively - Fig. 7.13i,j), however, no relationship was found with the other orders (p>0.05).

The aspect of the wall, categorised either on the basis of the four cardinal directions or on the basis of the four cardinal plus the four intercardinal directions, had no effect on insect abundance and richness, either total or by order (p>0.05).

7.5.5 Effect of adjacent land on insect populations on LW

The closeness and abundance of vegetation surrounding the living walls, the vehicle traffic volumes and the pedestrian traffic flows were categorised into four categories (from 0 'none' to 3 'high', see Table 3.2). These factors were not significantly related to total insect abundance or species richness (p>0.05). However, significant relationships were detected at the order level (Fig. 7.14).

There was a positive and significant relationship between the closeness and abundance of vegetation surrounding the living walls and Coleopteran abundance (R^2=0.19, $F_{1,21}$=5.52, p=0.027 - Fig. 7.14a), Coleopteran species richness (R^2=0.15, $F_{1,21}$=4.28, p=0.050 - Fig. 7.14b), and Hemipteran richness (R^2=0.46, $F_{1,21}$=16.97, p=0.01 - Fig. 7.14d), but not with Hemipteran abundance (p=0.065 - Fig. 7.14c). The closeness and abundance of surrounding vegetation was not significantly related to the abundance and species richness of Diptera or Hymenoptera (p>0.05).

Vehicle traffic levels were significantly negatively related to Coleopteran abundance (R^2=0.15, $F_{1,21}$=4.33, p=0.048 - Fig. 7.14e) but not richness (p=0.443 - Fig. 7.14f). The abundance and species richness of Diptera, Hemiptera, and Hymenoptera were not significantly related to the vehicle traffic volumes (p>0.05).

Pedestrian traffic flows did not significantly affect Hymenopteran abundance (p=0.545 - Fig. 7.14g) but did appear to significantly reduce the species richness (R^2=0.23, $F_{1,21}$=6.03, p=0.023 - Fig. 7.14h). The abundance and species richness of Coleoptera, Diptera and Hemiptera showed no significant relationship with pedestrian traffic volumes (p>0.05).

7.5.6 Multiple interactions between insects abundance and diversity and the green wall characteristics

MCA of all site data produced a solution in 2D with axis 1 accounting for 33.3% of the variation and axis 2 a further 22.2% of the variation (model: total chi-square=505.997, df=361, p<0.001 - Fig. 7.15). Subsequent dimensions individually extracted far less variation (Table 7.16).

The different living wall systems and locations are spread evenly across the axis and the origin. Changes in abundance largely coincided with richness for all specific taxa. Two taxonomic groups (Hymenoptera, Hemiptera) increased in value on Axis 1; the Diptera, in contrast declined on Axis 1 and largely resolved (to lower values) on Axis 2. The pattern for Coleoptera is intermediate between these three orders as is, understandably, the pattern for all insects.

Green wall characteristics (especially plant diversity, plant density and green wall age) seem to have more influence on insect populations than the surroundings. Changes in

Hymenoptera and Hemiptera richness and abundance largely accord with the increase in plant diversity, plant density and green wall age, and decrease with pedestrian traffic volumes and surrounding vegetation. Dipteran abundance and diversity show a very different pattern, occupy younger walls with lower plant diversity and density and is less sensitive to pedestrian traffic volumes. Diptera are less abundant and diverse where Hemiptera and Hymenoptera are dominant. Coleopteran abundance and richness follow the wall aspect and prefer north facing walls; whilst not being influenced by plant diversity and density or wall age. Vehicle traffic volumes, type of living wall system and location seem to have little effect on insect taxa than compared to the other investigated factors.

7.6 RESULTS – COLONISATION OF NEW LIVING WALLS BY INSECTS

7.6.1 Insect populations on a new living wall

On the new living wall, 364 insects were sampled over the five-sample period from June to August 2012. Thirty-three families and sixty-one species were identified from seven orders (Table 7.17). The most family-rich orders were Diptera (16 families) and Hymenoptera (9 families). The most species-rich families were Chironomidae (6 species), Pteromalidae (6 species), Braconidae (4 species) and Opomyzidae (4 species).

The order with the greater abundance were Diptera (163 individuals) and Hemiptera (84 individuals).

The families with the greatest abundance were Aphididae (81 individuals), Chironomidae (41 individuals), Lathridiidae (39 individuals) and Ephydridae (35 individuals). Fourteen families (42.4%) were singletons and nineteen families (57.6%) were represented by fewer than five individuals. Thirty species were singletons (47.6%) and seventy-one species (71.4%) were represented by fewer than five individuals.

No edge effects were evident on the new living wall, as the total insect abundance, the species richness and the abundance and richness by order were similar on the panels at either end of the living wall and on the panels in the centre of the wall ($p>0.05$, see Fig. 3.3 for further details on the wall design). The insect data were then aggregated by plant treatment (flowering treatment vs. non-flowering treatment) and height (low vs. high), in four groups.

7.6.2 Effect of height and vegetation composition on insect populations

Total abundance of insects was greater in the lower blocks (7.1 ±0.75) than in the higher blocks (3.3 ±0.47, $z=-3.59$, n7, $p<0.001$), as was the overall species richness (4.1 ±0.40, 2.3 ±0.33 respectively, $z=-3.01$, $n=7$, $p=0.003$). Abundance was greater in non-flowering treatment (6.1 ±0.71) than in flowering treatment (4.3 ±0.66, $z=-2.05$, $n=7$, $p=0.04$), whilst overall species richness was similar (3.6 ±0.40, 2.9 ±0.38 respectively, p=0.164). The combined effects of height and vegetation composition showed that total insect abundance and species richness in the non-flowering treatment were greater in the lower blocks than in the higher blocks, whilst there was no influence of height on insect abundance and richness in the flowering treatment (Fig. 7.16, Table 7.18).

The abundance and richness of Coleoptera and Diptera, the abundance of Hemiptera and the abundance and richness of Hymenoptera were significantly greater in the lower blocks than in the higher blocks when samples from both plant treatments were aggregated (see Fig. 7.17). Hemipteran abundance was greater in the non-flowering treatment than in the flowering treatment (z=-2.69, n=7, p=0.007), as was Hemipteran species richness (z=-2.67, n=7, p=0.008). Vegetation composition did not affect the abundance and richness of Coleoptera, Diptera or Hymenopteran (p>0.05).

The combined effects of height and vegetation composition affected the insect orders differentially. Abundance and richness of Coleoptera in the flowering treatment were greater in the lower blocks than in the higher blocks, whereas there was no influence of height on insect abundance and richness in the flowering treatment (Fig. 7.17, Table 7.19). Conversely, Dipteran abundance and richness in the non-flowering treatment were greater in the lower blocks than in the higher blocks, whilst there was no influence of height on abundance and richness in the flowering treatment (Fig. 7.17, Table 7.19). More Diptera were also caught in the non-flowering treatment than the flowering treatment in the lower blocks, whilst abundance was similar between the two-vegetation composition in the higher blocks (Fig. 7.17, Table 7.19). Hemipteran abundance and richness in the higher block were greater in the non-flowering treatment than in the flowering treatment; but there was no influence of vegetation composition in the lower blocks (Fig. 7.17, Table 7.19). The combined effect of height and vegetation composition did not have significant effect on Hymenopteran abundance and species richness (Table 7.19).

7.6.3 Colonisation over time

Overall abundance and species richness of insects increased over time from June to the end of August: they were significantly lower in the first two samples than in the following ones (Fig. 7.18, Table 7.20).

Coleopteran abundance and richness of significantly increased over time: Coleoptera were less abundant in the first two samples than the following ones, with the last one showing the greatest abundance compared to the others (Fig. 7.19a, Table 7.21); and the first three samples were less species rich than the last two samples (Fig. 7.19b, Table 7.21).

Dipteran abundance and richness increased over time but slightly decreased in the last sample. As such, the abundance and richness were lower in the first two samples than the three following samples (Fig. 7.19, Table 7.21). Species richness decreased significantly during the last sample, however abundance was similar (Fig. 7.19, Table 7.21).

Hemipteran abundance was not affected by the period of sampling, whilst species richness significantly increased in the third and the last sample compared to the first sample (Fig. 7.19, Table 7.21).

Hymenopteran abundance and richness significantly increased over time: abundance and richness were lower in the first two samples than the three following samples (Fig. 7.19, Table 7.21).

7.7 DISCUSSION

7.7.1 Insect populations on green walls

The results of this study indicate that green walls, either green façades or living walls, may be considered to have an abundant and diverse insect fauna (see also section 7.7.6). Common in urban areas (e.g. Cook & Faeth 2006; Toledo & Moreira 2008; Matteson *et al.* 2013), Diptera, Hymenoptera, and Hemiptera were the most abundant and rich insect groups found. Some animal groups considered as pests were present, such as Cecidomyiidae (gall midges, most abundant family of Diptera in GF) and Aphididae (whiteflies, most abundant family of Hemiptera in both GF and LW). Nearly all Hymenoptera were wasps or parasitoids (either primary or hyperparasitoid) of various groups such as aphids, scale insects, leaf miner, etc. (Polaszek pers. comm.), therefore, the high abundance and diversity of Hymenoptera on green walls may be related to the overall abundant and diverse insect communities on green walls, providing potential high parasitoids-host diversity.

Abundance of Lepidoptera (see also section 8.2) may be proportionally lower than the other insect orders in urban areas (Shortall *et al.* 2009), partly because of the large number of specialist species that have been shown to be negatively related to urbanisation or any human disturbance (Soga & Koike 2013; Summerville 2014). In addition, the small abundance of Lepidoptera found here may be related to the sampling technique as sticky, light and pheromone traps have been shown to be better at capturing Lepidoptera than suction sampling (Pedigo & Buntin 1993). Moreover, the relatively low abundances of both Lepidoptera and Coleoptera in the study may be related to the fact that they are both sensitive to dispersal barriers (e.g. vehicle traffic and lack of nearby vegetation - see Bräuniger *et al.* 2010) which makes isolated green walls harder to colonise (see also section 7.7.6 for comparison between GF and LW).

The biodiversity of Psocoptera in urban areas is typically poorly documented as it is not a well-known order (Zapparoli 1997). However, the proportionally large abundance of this taxon is an indicator of the important presence of organic material due to the decaying vegetation within green walls, whether they are green façades or living walls (Kanervo & Kozlov 2014, see also section 8.1.1).

7.7.2 Effects of sampling technique and identification method on the estimation of insect populations on green walls

Two potential biases may have affected the study: the sampling technique used and the identification by morphospecies.

According to Harper *et al.* (1993) and Wade *et al.* (2006), suction sampling is likely to miss "large-bodied" insects. However, with the same methodology, the suction device was able to capture small specimens such as Collembola, and snails of respectable size (e.g. adult *Cornu aspersa*, see Chapter 4 for further details). Additionally, the analysis of the spider species composition sampled by both visual searching and suctions suggested that the two methods were sampling different strata (the outer surface of the foliage only for visual searching, the outer surface of the foliage and within it for suction, see section 6.7.2). Therefore, vortis suction seems to be a suitable sampling method for estimating insect fauna using green walls, although it is likely that it sampled only the insects within the foliage, and not the insects flying above the foliage (see also sections 1.6.2 and 7.2).

For specimens where no external morphological differences could be seen, individuals were aggregated into a single morphospecies. As such, species with sexual dimorphism may have been separated into two morphospecies and sibling species may have been grouped together. Therefore, the risk is jointly the overestimation and underestimation of insect richness (Derraik & Closs 2002; Obrist & Duelli 2010). The use of morphospecies as surrogates for species is often employed to overcome the complexity of identification to species, which is very time-consuming and requires a high level of taxonomic expertise (Oliver & Beattie 1993; Derraik & Closs 2002; Borges & Brown 2013). As a result, it is common practice in biodiversity studies to use the morphospecies approach which has been shown not to compromise the scientific accuracy (see Oliver & Beattie 1996; Derraik & Closs 2002). However, Derraik & Closs (2002) showed that morphospecies separation is not accurate for some groups in which species identification is problematic even for experienced taxonomists. This was, for example, the case for Coleoptera in Derraik & Closs' study (2002) where the best result of a correct separation frequency of morphospecies compared to taxonomic species was 77.8% for Curculionidae (weevils). Therefore, some taxonomic training is advisable before identifying insects, even to the morphospecies level. Because of the high abundance of Hymenoptera in green wall samples, training to identify specimens of this group was given by Dr. Andrew Polaszek from the Natural History Museum of London, whilst previous research projects provided the author with experience in Dipteran identification.

7.7.3 Value of green façades for insects

As expected in the hypothesis, insect abundance and richness were greater on GF than on bare walls (6404 vs. 124 individuals, 208 vs. 2 species). Insect community was predominantly comprised of Hymenoptera (1599 individuals), Diptera (1558 individuals) and Hemiptera (1324 individuals) which were also the more species rich orders (especially Diptera).

The finding of Bartfelder and Köhler (1987, in Köhler *et al.* 1993) suggested a high proportion of Coleoptera and Diptera on GF in Berlin (with no mention of Hemiptera and Hymenoptera). According to their study, four species represented more than fifty percent of the total abundance of Coleoptera (Anobiidae *Mesocoelopus niger* 7.2%, *Ochina ptinoides* 24.8%, *Ptinus fur* 10.3%, and Nitidulidae *Meligethes aeneus* 8.8%), whilst a single species represented fifty-two percent of the total abundance of Diptera (Sciaridae *Lycoria modesta* at larval stage). Similarly here, four morphospecies represented more than fifty percent of the total abundance of Coleoptera on GF (belonging to the families Carabidae 16.0%, Curculionidae 7.6%, Dermestidae 11.1% and Staphylinidae 19.4%). However, ten species represented fifty-percent of the total abundance of Diptera (belonging to the families Anisopidae 6.5%, Cecidomyiidae 10.8%, 5.8%, 4.1% and 4.0%, Lonchopteridae 3.3%, Phoridae 4.1%, Psychodidae 5.7%, 3.5% and Sciaridae 5.4%). As with Bartfelder & Köhler (1987, in Köhler *et al.* 1993), a small number of species were found to dominate the Coleopteran fauna in this study; in contrast, a similar pattern to that of Köhler was not found for the Diptera. Unfortunately Barfelder & Köhler's study (1987, in Köhler 1993) was not accessible to further investigate the reason for this difference.

7.7.3.1 Seasonality effect on insect populations on green façades

Contrary to the hypothesis, only the species richness of Diptera and Hemiptera were affected by seasonality. Dipteran richness was greater in the autumn, probably due to the presence of flowers and therefore nectar and pollen sources on ivy (Metcalfe 2005), whilst, in contrast, Hemiptera were more species rich in the summer, perhaps due to the warmer temperatures and/or the longer day length (Coombs 1996; Ott & Azevedo-Filho 2006). Coleopteran abundance and richness may have been too low to allow the identification of seasonal difference, while Hymenoptera were as rich and abundant in the summer and in the autumn.

Due to the balancing of the richness of Diptera and Hemiptera between the seasons, the overall insect richness was similar in the summer and in the autumn. In addition, seasonality had no effect on the overall abundance and abundance by order. These findings suggest that GF would be as attractive for insects in both seasons but that different insect groups will use them over time.

7.7.3.2 Influence of foliage type and vegetation composition on insect populations

Total abundance and richness of insects were greater in evergreen foliage than in deciduous foliage, both when data from both seasons were aggregated or in each season as expected. However, there were relatively few study sites with deciduous foliage and it is possible that the validity of the findings could be questioned despite the significance of the results. Nevertheless, the findings do follow expectations, as the greater level of cover on GF with evergreen foliage (often made of *Hedera sp.*) compared with deciduous foliage (often made of light cover plants such as *Parthenocissus spp.*) may be expected to provide enhanced shelter and protection for insects, especially in the autumn.

Coleoptera were more abundant in evergreen foliage than deciduous foliage in total and in the autumn but similar in the summer. The absence of any difference in the summer may be related to the small abundance of Coleoptera found on GF during that season, whilst differences between the foliage type in total and in the autumn may be related to the more ‘woody structure’ of evergreen GF which is more attractive to Coleoptera (Stapp 1997; Tyler 2007). Dipteran abundance and richness were greater in evergreen foliage than in deciduous in total and in each season and in addition Dipteran richness in evergreen foliage was greater in the autumn than in the summer. The study of vegetation composition of green façades showed the greater attractiveness of the evergreen *Hedera spp.* for insect fauna compared to other climber species. This attractiveness was especially obvious in the autumn and for the orders Diptera and Hemiptera. The more dense cover of evergreen foliage, which provides shelter, may be related to this greater attractiveness, especially in the autumn where the temperatures start to drop (data collection took place before leaf fall, to compare the value of both foliages in the autumn). Furthermore, the presence of nectar and pollen sources with ivy flowers blossoming in the autumn (Metcalfe 2005) may also explain the greater attractiveness during that season (Jacobs *et al.* 2009), particularly for Hemiptera which were not affected by the foliage type but were more species-rich in wall with polyculture *Hedera spp.* than in other GF. When data from both seasons were aggregated and in each season, Hymenoptera were not affected by the type of foliage or whether the GF was made of *Hedera sp.* or not, although ivy pollen has been shown to be the most prominent diet of honeybees in the autumn (Garbuzov & Ratnieks 2014). This absence of any significant influence of whether the vegetated wall was made of *Hedera sp.* or of other species on Hymenoptera may be related to the high variability of abundance and richness of this order between the different study sites and the dominant abundance of wasps found in the samples. It also suggests that other factors, not identified here, make deciduous foliage as attractive as evergreen foliage for this order.

Whether the vegetation was composed of a monoculture or a polyculture had no effect on insect abundance or species richness, either in total or by order, contrary to what is usually found in literature (e.g. Southwood *et al.* 1979; Corbet 2001). This may be due to the dominant monoculture nature of the study sites (mainly *Hedera sp*.). Abundances and richness of insect orders were greater on GF with *Hedera sp.* (either a single or diverse species) than on GF with other species (either mono- or polyculture). This finding suggests a stronger influence of the vegetation composition over the vegetation richness on use by insects (Ings & Hartley 1999; Galle *et al.* 2000; Dumont *et al.* 2009) and confirms the value of ivy to Diptera, Hemiptera and Hymenoptera (Metcalfe 2005; Jacobs *et al.* 2009; Garbuzov & Ratnieks 2014).

7.7.4 Value of established living walls for insects

The similarity in abundance and richness of insect orders between Birmingham and London suggest that big cities homogenize the physical and biological environments to a certain gradient (McKinney 2006; Kowarik 2011). On living walls, insect community was predominantly comprised of Diptera (533 individuals), Hemiptera (451 individuals), and Hymenoptera (217 individuals) which were also the more species rich orders.

7.7.4.1 Effect of the LW systems on insect populations

The type of LW system had no effect on total insect abundance or richness, however, it had different impacts on insect orders. There were relatively few study sites with horizontal plant box systems or plant pot systems and it is possible that the validity of the findings could be questioned despite the significance of the results. No previous studies on LWS were found with which to compare the results; however, several inferences may be drawn. Coleoptera were not affected by the different LWS, and this is probably because few Coleoptera were found during the study. Diptera were more abundant in the horizontal plant box and the plant pot systems than in the rockwool unit, angled plastic module and green screen systems. As most of Dipteran larva are litter-feeding (Frouz & Šimek 2009; Kaneda *et al.* 2013), this finding may be related to the different levels of access to the growing media and the potential for leaf litter, which may be greater in the horizontal systems, i.e. where dead leaves are more likely to be retained and where there is a greater area of growing media exposed than the systems where plants are growing vertically (rockwool units, angled plastic modules, green screens). Conversely, Hemipteran abundance and richness were greater in the rockwool units and the angled plastic modules than in the other living wall systems. This higher attractiveness of the two systems may be related to their denser cover foliage or to other factors not identified here. Hymenoptera were not affected by the different LWS; this may be due to the large variability found in each system perhaps suggesting the influences of factors not related to the system design (see below).

7.7.4.2 Effect of period of sampling on insect fauna

The total abundance and richness of insects increased throughout the sampling period, significantly in Birmingham and not significantly in London. Period of sampling had no effect on the abundance and richness of the different insect orders in Birmingham but Diptera were more abundant in London from the second sample onwards (i.e. from the end of July). In Birmingham, this could mean that the species fluctuations were balancing each other out throughout the summer and that the principal emergence of insects happened prior the beginning of the study. Although it may also be the same explanation in London, it is also possible that a Dipteran emergence occurred at the time of the second sample.

7.7.4.3 Effect of the wall characteristics on insect populations

Apart from aspect, which had no influence on insect orders abundance and richness, LW characteristics had differential effects.

The age of the wall was negatively related to Dipteran richness as has been shown for hedges in rural areas (Maudsley 2000). This may be related to their dispersal ability, as their needs could be fulfilled by different green infrastructure components (Hennig & Ghazoul 2011). It suggests that some species of Diptera are using GW among other structures as additional resources and not exclusively.

The area of wall vegetation surface was positively related to Coleopteran richness and Hemipteran abundance and richness (Tully *et al.* 1991; Sasal *et al.* 2010; Saunders *et al.* 2013), whilst it did not affect Diptera and Hymenoptera, which appear to be more sensitive to the levels of floral resources than vegetation cover *per se* (Hennig & Ghazoul 2011; Matteson *et al.* 2013).

In this study, the plant richness and density were negatively related to Dipteran abundance and richness, whereas the other orders were not affected. This finding is similar to some previous studies (e.g. Hennig & Ghazoul 2011) but is contrary to others (e.g. see Scherber *et al.* 2014). This variation of response has been shown to depend on the Diptera species (Haddad *et al.* 2011; Scherber *et al.* 2014; Araujo 2014).

The high abundance and richness of Hymenoptera found in this study were affected by none of the LW characteristics investigated and imply the influence of other factors than the ones identified here, or possibly the adaption of Hymenoptera to a wide range of urban habitat.

7.7.4.4 Effect of surroundings on the insect fauna of living walls

Surroundings had no effect on total insect abundance and richness but had differential effects on the insect orders using living walls.

Coleopteran abundance and richness, and Hemipteran richness were positively related to the surrounding vegetation, whilst the vehicle traffic was negatively linked to Coleopteran abundance. Vehicle traffic may affect Coleoptera by making their dispersal move difficult from other sites, especially for species with no flight ability (Yamada *et al.* 2009), and has also been shown to be linked to reduced abundance of diet-generalist species and reduced mean body length (Melis *et al.* 2009). Hemiptera were less likely to be influenced by vehicle traffic levels due to their ability to fly. These relationships may indicate that Coleoptera and Hemiptera use green walls for one or more functions (e.g. protection, feeding, mating) but not as their exclusive habitat and that they may use several green infrastructure components during their life-span in urban areas (see Dennis 2010). Diptera and Hymenoptera were not influenced by the surrounding vegetation or the vehicle traffic volumes. As Dipteran richness was shown be negatively related to the age of the wall and none of the LW characteristics influenced the abundance and richness of Hymenoptera, it may suggest that the high dispersal ability of these orders allows them to access resources from a wider area (see Maudsley 2000).

Living walls were accessible to pedestrians in varying degrees, either to all city-dwellers in public areas or only to the private owners. Pedestrians could pass by but also linger in front of the living walls and touch the plants. Hymenopteran richness was negatively related to pedestrian flows, suggesting that many species of Hymenoptera are affected by human disturbance as inferred in previous studies (see Curtis & Stamp 2006; Michelutti *et al.* 2013) and may not colonise a wall likely to have strong human presence nearby. Conversely, as Hymenopteran abundance was not affected by pedestrian, this suggests that some species, not as affected by human presence as others (see Curtis & Stamp 2006), will thrive in a habitat with little competition with other species from the same order.

7.7.4.5 Insect taxa respond more to green wall characteristics than to specific vertical greening systems

In the MCA analysis, as the different systems are spread evenly across the axis and the origin, it is not possible to identify any particular system as being superior to the others in terms of insect diversity and abundance. Insect taxa appear to responde more to green wall characteristics such as plant diversity, plant density and green wall age than LWS. As such, to enhance Hymenoptera and Hemiptera the best system would be one with high plant diversity and density, such as how the angled plastic module is currently designed. However, this would limit the abundance and richness of Diptera which were thriving in less diverse green walls such as the plastic modular system or the horizontal planter box system. The plant diversity and density can be modified in all LWS that were studied here; as such, it appears that it may be possible to design any wall to enhance or limit specific insect orders.

Although the surroundings play a role in determining the insect taxa living on green walls (especially pedestrian traffic volumes), they have less influence than the green wall characteristics which may indicate the level of isolation of the habitat created by green walls (see also section 2.4.2).

7.7.5 Colonisation of new living walls by insects

The monitoring of the new living wall installed in Staffordshire University gave useful information on the first species which colonise a newly planted GW in the urban environment. The increasing insect orders abundance and richness over time highlight the on-going colonisation which appears to still be incomplete 14 months after the installation of the wall.

No differences were found in the abundance and richness of insect in total and by order between the edges of the wall and its core, suggesting the absence of an edge effect. The latter is typical of some ecosystems like urbanised forests and small islands (e.g. Östman *et al.* 2009; Gaublomme *et al.* 2014) and may depend on the animal species (e.g. Olson & Andow 2008; Murphy *et al.* 2009). It may also be possible that the surface area of the vegetation is too small to provide a proper core, i.e. there is no surface area not affected by edge effect (see Dramstad *et al.* 1997; With 1997), and the living wall may therefore be only colonised by edge- and generalist-species (Dramstad *et al.* 1997; With 1997).

As hypothesised, insect populations were affected by the height: abundance and richness of all the orders were greater in the lower blocks than in the higher blocks. Contrary to what was expected, when the flowering and non-flowering treatments were compared irrespective of height, insects were more abundant and rich in the non-flowering treatment than in the flowering treatment, although only significantly so for Hemiptera (mostly composed of Aphididae). This may be due to structural differences such as heterogeneity and density of cover, but also to differences in palatability of the two types of foliage (e.g. Reader & Southwood 1981; Basset 1994). The combined effect of height and vegetation composition showed that the height had more effect on insect populations than the plant treatment. This finding indicates the presence of a vertical gradient influencing insect distribution, as found in hedges and forest canopies (e.g. Maudsley 2000; Graham *et al.* 2012; Vodka and Cizek 2013; Maguire *et al.* 2014), although this effect is usually more important in winter (Maudsley *et al.* 2002). In a public area with high pedestrian flow, such as the University campus where the new living wall was installed, insects could be expected to avoid human disturbance and use the wall at a higher level, especially Hymenoptera which showed a strong negative relationship with pedestrian flows. However, the greater insect abundance and richness in total and by order in the lower blocks (between 0.2 m and 1.4 m high) than in the higher blocks (between 1.4 and 2.6 m high) suggest the effect of wind turbulence (Maudsley *et al.* 2002), as according Hang *et al.* (2013) the wind velocity in urban area reaches a threshold around 1.5 m high.

7.7.6 Comparison between green façades, livings walls and green screens

Direct comparison between green façades and living walls cannot be carried out, as surveys were made in different years and the study sites differed in many ways (see sections 3.1 and 6.7.5); however, several inferences may be drawn. Table 7.22 summarises the proportion of abundance and species richness by family on green façades, living walls and green screens in the summer. In green façades, Diptera, Hymenoptera, and Hemiptera were dominating, accounting for 30.6%, 26.8% and 21.3% of the total insect abundance respectively. In living walls, Diptera and Hemiptera were mostly dominating compared to Hymenoptera (38.1%, 32.2%, and 15.5% of total abundance respectively). In green screens, Hymenoptera, Diptera and Hemiptera were the most abundant orders (35.6%, 31.1% and 26.1% respectively). Dipteran and Hymenopteran species richness contributed the most to the total species richness on green façades (31.2%, 29.4% respectively), on living walls (37.2% and 29.2% respectively) and on green screens (45.76% and 25.42% respectively).

The total species richness found in the summer, 170 species on GF and 137 species on LW, and the average species richness found, 22.89 ±1.4 on GF and 20.4 ±1.13 on LW, may suggest that insects use GF and LW equally. However, comparison of family composition between GF and LW revealed that 28 families were only found on green façades (of which 2 Coleoptera, 13 Diptera, 7 Hemiptera and 4 Hymenoptera) and 14 families were only found on living walls (of which 3 Coleoptera, 3 Diptera, 1 Hemiptera, and 4 Hymenoptera) (Table 7.22). For example, Syrphidae and Vespidae were only captured on green façades, perhaps due to the higher human disturbance on living walls (see Trant *et al.* 2010; Michelutti *et al.* 2013). These differences suggest a discrete complementarity between GF and LW, and it is probably due to a combination of their specific attributes and the effect of indirect factors, such as the year of sampling or the human disturbance being far greater around LW than GW. For example, the families Sciaridae, Chloropidae and Chironomidae were proportionally more found on LW than on GF, certainly due to the greater moisture provided by the presence of growing media along the vertical axe.

Whilst insect families and species were well represented on GF (only a fifth of the families and a third of the species had fewer than five individuals), approximately half of the families and a quarter of the species were represented by fewer than five individuals on LW. The insect ratio abundance/richness was thus smaller on LW (10.21) than on GF (30.79) suggesting that

LW are likely to attract a more diverse fauna than GF, even when installed in more human disturbed areas (see sections 3.1 and 6.7.5 for further detail on the GW environment). Habitat restoration was shown to enhance recovery of species richness and community structure prior to increases in abundance (see Grégoire-Taillefer & Wheeler 2011). Similarly, it is likely that following the installation of a GW, insect richness may increase first before being followed by an increase of the abundance of each species. When foraging sites are available in the surroundings, species groups using the habitat only for shelter may colonise faster than those using the habitat for both food and shelter (Chapman 2007).

There was a significant relationship between plant richness on LW and both Dipteran abundance and richness. Conversely, whether the GF was composed of a monoculture or a polyculture had no effect on Diptera. The same difference appeared for spider abundance and richness (sections 6.4.7, 6.5.6, and 6.7.5) and may be due to the greater diversity of plants on LW (minimum five different genera and fourteen on average); whereas the GF had a maximum of six different genera.

The vegetation area was not related to insect abundance and richness in total and by order on GF but was related to Coleopteran richness and Hemipteran abundance and richness on LW. This may be related to the higher mean vegetation surface area on LW (65.9 ±3.09) compared to GF (21.4 ±2.81), providing more of a given resource.

The lower insect abundance and richness in green screens compared to green façades and living walls can be explained by their vegetated structure, kept narrow for fencing purposes.

The direct and indirect factors influenced the insect orders differently. For example, Dipteran abundance and richness were influenced, either positively or negatively, by direct factors (e.g. type of LWS, age of the walls, plant density and richness, type of foliage) but not by the indirect factors. Conversely, Hymenoptera were only affected by indirect factors (as the pedestrian traffic) and none of the LW characteristics. Coleoptera and Hemiptera were influenced both by direct and indirect factors suggesting that the use of GW was not exclusive but that dispersal into and out of them is an important process (Driscoll *et al.* 2010).

Wall aspect had no effect on insect abundance and richness on green façades in total or by order. There are obvious abiotic factors related to aspect (insolation, wind, solar exposure etc., see Gardiner & Dover 2007) which are likely to create more favourable conditions in some aspects than others. However, no relationships was found with the data and this is perhaps because the vegetation and the physical structure of the wall (either GF or LW) created a microclimate (Sternberg *et al.* 2011) sufficient for insects to settle on any aspect. No previous studies on the effect of the aspects of hedgerows, building façades and vertical structures were found on this subject to discuss it further.

7.7.7 Insect populations of green walls compared to other ecosystems

A study by Hagedoorn & Zucchi (1989), reported in Köhler *et al.* (1993), investigated the invertebrate biodiversity of different type of green façade: old and young plants of *Vitis sp.* grapevine and *Hedera sp.* ivy. The comparison of invertebrate abundance between the old and young GF highlighted the greater attractiveness of woody features as living spaces (in Köhler *et al.* 1993). The findings of the present study suggested that LW composed of herbaceous plants may attract an insect fauna as abundant and diverse than the insect fauna found on the woodier GF. Alongside Köhler *et al.* (1993), the findings of the present study suggested that GW could be used as habitat by invertebrates in urban areas and furthermore suggest that some animal groups will favour GF for some of its characteristics, whilst other will favour LW. No previous studies on the spider fauna of living walls have been reported in the literature, and as such, no direct comparison between the data presented here and other studies are possible. Other building related structures, such as green roofs, have been studied for their value to enhance biodiversity in urban areas. Whilst the methods of collection are quite different because of the nature of the structures (e.g. horizontal compared to vertical), they appeared to attract different species richness according to the published work of Kadas (2011) and Madre *et al.* (2013). On green roofs, either muscinal, herbaceous, arbustive, or brown (i.e. designed to emulate brownfield habitats), the species richness are estimated to be as followed: Coleoptera nine to eleven species, Hemiptera ten species, and Hymenoptera twenty-four species (Kadas 2011; Madre *et al.* 2013). The richness of Coleoptera, Hemiptera and Hymenoptera are estimated to be of eighteen, thirty-eight and sixty species respectively in this study. These findings suggest that GW may be used by a wider range of insect species than green roofs. This may be related to their easier accessibility, the greater plant diversity, and the greater shelter from the wind. Green walls may also act as stepping stones for dispersal more easily than green roofs, and thus enhance the connectivity between different green spaces.

Most of the potential direct and indirect factors examined had little or no influence on total abundance or species richness. However, aggregating data in this way can obscure the responses of different species groups to those factors. At the order level, there were clear influences, and these findings suggest that the environmental and physical structure of a green wall may affect the insect orders using it differentially. In this way, it may be possible to design green wall systems to promote certain animal taxa over others, for example, to deliver specific ecosystem services such as providing resources to support communities of pollinators, to create structures that support pest-reducing predators, or to create a visually appealing vertical landscape that contributes to the sustainability of urban biodiversity.

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CHAPTER VIII

SYNTHESIS, IMPLICATIONS AND CONCLUSIONS

8. SYNTHESIS, IMPLICATIONS AND CONCLUSIONS

This chapter synthesises the main findings from the research reported in the previous chapters, followed by a critical analysis of the methodology. The influence of the green wall design on its biodiversity is discussed to highlight the direct implications on the green wall management and the links to the planning and public policy. The thesis ends with recommendations for further work.

8.1 SYNTHESIS OF THE PHD RESULTS

The enhancement of urban animal biodiversity by green walls (GW) is a benefit that is often assumed by those involved in the green wall sector (manufacturers, developers, installers, policy makers, consultants, etc.). However, although some information existed on the invertebrate biodiversity of green façades in the German literature, no empirical data could be found on living walls as they are relatively new structure. The main aim of this research was to provide direct empirical evidence of the biodiversity value of green walls, focusing on green façades (GF) and living walls (LW) specifically (see section 2.2.1 for definitions) and to record and quantify the animals that live on and interact with these walls. The study highlighted that green walls are used by vertebrate and invertebrate groups, with animal taxa being influenced differently by the structural and environmental composition of green walls (see sections 3.1, 4.3, 5.3, 6.3 and 7.3 for further details).

8.1.1 Structural factors influencing the use of green walls by animal taxa

The influences of the different investigated factors on the studied taxa are summarised in Table 8.1. In the present study, the (vertical) **surface area** was found to be only significantly related to Coleopteran and Hemipteran abundance and richness, whilst abundance and richness of Diptera, Hemiptera, and spiders (and especially sheet- and tangle-weavers) were found to be related to the **plant richness and plant density** of established living walls (sections 4.4.4, 5.4.5, 5.4.7, 6.4.7, 6.5.7, 7.4.5 and 7.5.5). **Structural heterogeneity of vegetation** can be expected to be related to plant richness and has been shown to have an important influence on invertebrate communities (Rypstra & Carter 1995; Labaune & Magnin 2002; Cobbold & MacMahon 2012). As such, the greater influence of plant richness on the use of GW by animals, compared to vegetation surface area, may be related to the structural heterogeneity of vegetation.

In the new living wall set on the University campus, the animal use of a non-flowering **botanical composition** was compared to a flowering botanical composition (see details of the botanical composition in section 3.1.3). The presence of flowers was expected to attract more invertebrates than the non-flowering treatment for a similar plant richness. However, snail, insect and spider populations overall, and more specifically Diptera, Hemiptera, orb- and sheet-weavers were more abundant and rich in the non-flowering treatment than the flowering treatment (sections 5.5, 6.6.2, 7.6.2). Again, this preference may be related to the structural heterogeneity of the vegetation as, in the flowering treatment, *Heuchera sp.* was dominating the canopy and thus homogenising the surface, whereas in the non-flowering treatment, the three plant species (*L. nitida*, *P. vulgare* and *P. setiferum*) developed a varied lateral structure. Although no influence was found on birds, perhaps due to the small abundance, the botanical composition of green walls may influence its bird fauna as it does in hedgerows (see Best 1983, O'Connor 1987, MacDonald & Johnson 1995 in Hinsley & Bellamy 2000, Green *et al.* 1994).

Green façades (GF) made exclusively of ***Hedera sp*.** were more attractive for insects overall, and especially for the taxa Diptera and Hemiptera, than GF made of other plant species (section 7.4.4). This greater attractiveness was especially evident in the autumn. These findings may be related to the availability of food sources (pollen and nectar) and the shelter this plant genus provides (Diefenbach & Becker 1992; Metcalfe 2005; Jacobs *et al.* 2009; Garbuzov & Ratnieks 2014), but also to its evergreen foliage. For example, the **type of foliage** (evergreen vs. deciduous) was shown here to influence the abundance and richness of birds, snail, spider and insects (especially Coleoptera and Diptera) (sections 4.4.3, 5.4.4, 6.4.6, 7.4.3). This effect, which was more, or only, significant in the autumn and winter, is likely related to the higher protection provided by evergreen foliage than deciduous. Contradicting the positive relationship found between plant species richness and invertebrates communities, these results suggest that depending on the time of year and the resources provided by the vegetation, green walls with **monoculture** may sometimes be used by more animals than GW with polyculture (see sections 6.7.1.3 and 7.7.3.2). For green façades, the **height of a wall** may be related to its age depending on the plant species and the maintenance, whereas it is often a set characteristic for a living wall (see section 2.2.1 for definitions of GF and LW). Web-weaving spider abundance and insect richness and abundance in total, and by order, were found to be influenced by the height of wall, and birds were only found on the upper half of walls (sections 4.4.4, 6.6.2, 7.6.2). However, it should be noted that the scale of the comparisons between birds and invertebrates were different (the entire green wall area and the adjacent roof for birds, and ground to two meter high for invertebrates, see section 3.2). Shrub height has been shown to affect the abundance and species of birds, Coleoptera, Hemiptera, Hymenoptera (solitary wasps and bees), and Lepidoptera (Meiners & Obermaier 2004; Littlewood *et al.* 2006; Loyola & Martins 2008; Campbell 2011; Berg *et al.* 2013; Gow & Stutchbury 2013).

No relationship is usually found between the **age** of a green feature, such as a hedge and the Diptera population using it, perhaps due to the large dispersal ability of the latter (see Maudsley 2000). In addition, the age of hedges has been related to their vegetation diversity and richness (Cameron *et al.* 1980). This dual information may explain the negative relationship found in this study between LW age and Diptera and the negative relationship between Diptera and plant richness (sections 7.5.4, 7.7.4), the latter of which has been shown to be dependent on the plant and the animal species (Scherber *et al.* 2014; Araujo 2014). The age of the LW was positively related with spider abundance, species richness and abundance of sheet- and tangle-weavers (section 6.5.6). This may be explained by two elements: as seen above and in section 6.5.6, abundance and richness of spiders, especially of web-weavers, increases with increasing plant richness probably due to the greater structural diversity preferentially selected by web-building species (Rypstra *et al.* 1999). Furthermore, the overall abundance and richness of the insect community increases with increasing plant diversity, either plant species richness or plant functional group richness (Siemann 1998; Gill *et al.* 2014), depending on the botanical composition (Haddad *et al.* 2001). By influencing the abundance of available prey, plant diversity impacts on higher trophic levels, e.g. predators such as spiders, thus stabilising the foodweb dynamics (Haddad *et al.* 2011).

The **type of living wall system** (LWS, i.e. angled or horizontal plastic modules, rockwool units, plant pots) was found to influence the abundances and richness of Diptera, Hemiptera, snails, and spiders (orb-, sheet- and tangle-weavers) differentially (sections 5.5, 6.5.4, 7.5.2). Snails and many insect species rely on soil and litter for wintering and/or larval/pupal stages (Lonnve *et al.* 2006; Qi *et al.* 2008; Szybiak & Błoszyk 2009; Clergeau *et al.* 2011). As such, the degree of access to the growing media may directly influence the invertebrate biodiversity. The accessibility would depend on the type of LWS: e.g. no, or little growing media on felt-layer systems (typically, during installation the majority of growing media is removed from around the roots), little access to it on rockwool units, whilst with plastic modular systems, access can vary between little to substantial depending on the specific system. This may explain the higher abundance and richness of Diptera in the horizontal systems (horizontal plant boxes and plant pots) as they need access to the decaying vegetation and the growing media which are evident in these systems, as well as their negative relationship with the plant density (sections 7.5.2, 7.5.4). Hemiptera were more abundant and rich on a system with little access, if any, to the substrate (rockwool units), which suggests a greater influence of the plant cover over the access to the growing media (sections 7.5.2, 7.5.4). The greater abundance and richness of spiders (and the greater abundances of sheet- and tangle-weavers in particular) on the rockwool units and the angled plastic modules may be related to the higher plant density of these systems compared to the others (sections 6.5.4, 6.5.6). No previous studies on the animal fauna of living walls have been reported in the literature, and therefore no critical analysis comparing the present data to other studies is possible.

Seasonality was shown to affect the abundances of birds and spiders overall, the richness of Diptera and Hemiptera, the age structures of snail and spider, the spider species composition and the relative abundance of web-weavers (orb, sheet and tangle) (sections 4.4.3, 5.4.2, 6.4.2, 6.4.6, 7.4.2-3). This effect is probably related to the type of foliage and the dominance of *Hedera sp.* on the GF, but also to the seasonal changes in species composition between summer, autumn and winter (Hauge 2000; Gudleifsson & Bjarnadottir 2004).

8.1.2 Environmental factors influencing the use of green walls by animal taxa

A positive relationship was found between the abundance of **surrounding vegetation** and the abundance and richness of birds, Coleoptera, and Hemiptera on green walls (sections 4.4.1, 7.5.5). Green walls were also shown to facilitate the use of the surrounding vegetation by birds, with more birds found in the vegetation around a green wall than in the vegetation surrounding a bare wall (section 4.4.1). These findings suggest dispersal between urban green features (see Green *et al.* 1994; Angold *et al.* 2006).

On LW, the **vehicle traffic** negatively affected the abundances of Coleoptera and spiders (sections 6.5.7, 7.5.5). This influence on invertebrates may be related to, amongst other things, related air turbulence (Minoranskij & Wojciechowski 1988; Arevalo & Newhard 2011) and traffic volume increasing mortality by potential collisions (Skórka *et al.* 2013). Varying in intensity during the day and on a weekly basis, traffic may indirectly affect the animal fauna on GW by creating a physical barrier between walls and other GI components.

Direct interaction between **pedestrians** and the wall vegetation, for example by touching, may be directly affecting the use of the GW by invertebrates, for example by interfering with the flower visitation rate (Leveau 2008). Hymenoptera and spiders (especially sheet- and tangle-weavers) may be particularly affected as they were found in fewer numbers in walls with high and frequent human presence (sections 6.5.7, 6.7.3.3, 7.5.5, 7.7.4.4). Probably due to the higher noise levels (see Fernández-Juricic 2000), pedestrian traffic was shown to affect the productivity of breeding of several bird species (e.g. Kight *et al.* 2012; Polak *et al.* 2013) and induced changes in behaviour, including modified foraging and perching behaviour (Laiolo 2002; Slabbekoorn & Ripmeester 2008; Dowling *et al.* 2011). This may be the case in this study as the use of green façades by birds was shown to be related with the time of day which could be linked with the human disturbance (section 4.4.2). Along with pedestrian traffic, maintenance actions on walls are likely to have a negative impact on animal population (see section 8.4 for further details).

Despite the limitations of the sampling method preventing comparative analysis, very few species appeared to use both GF and LW (see sections 5.6.7, 6.7.5 and 7.7.6). For specific details on the response of the different animal groups to the GW characteristics and the influence of the local environment, please refer to chapter 3 for birds, 4 for snails, 5 for spiders and 6 for insects.

8.2 COMMENTS AND RECOMMENDATIONS ON METHODS USED IN GREEN WALL RESEARCH

Limited sampling techniques are available for the investigation of the invertebrate fauna of green walls. Due to the high pedestrian traffic near them and the potential for fixed traps to be removed by people, as was observed during the pilot study, passive traps such as gutter, or non-sticky traps were not used (see also section 1.3). Beating was not an option on living walls because of the potential damage to the plants and due to the modules behind the plants hampering the process, and sweep-net use could not be standardised during the pilot study, especially for insects. Consequently, visual searching and suction sampling were used for the snail and spider surveys, supplemented with web counts for the latter (see sections 5.3.2 and 6.3.2 for further details). Visual searching alone was not possible for insects on foliage as capture was necessary to achieve identification (hand picking was used for snails and a combination of tuning fork/pooter was used to capture spiders) and hence, only suction sampling was carried out using a material suction sampler. As such, the small abundance of Lepidoptera in this study (see Tables 6.2, 6.11, 6.12 and 6.16 and section 7.7.1 for further details) may be partly explained by the use of suction sampling, as this trap was shown to be less efficient than sticky, light and pheromone traps for capturing adult Lepidoptera (Pedigo & Buntin 1993).

The influences of the investigated sampling methods on in the evaluation of the snail and the spider populations on green walls are summarised in Figure 8.1. Visual searching and suction sampling were found to sample similar species richness and abundances of snails (section 5.4.2) and similar species richness of spiders (section 6.4.5). If empty webs were counted, the two sampling methods estimated similar spider abundances, whereas if only specimens (identifiable or not) were considered, suction sampling captured more spiders than were observed in situ. Although their efficiency may be comparable in terms of abundance and species richness, the two methods sampled different age groups and species composition. Suction sampled more juvenile snails and spiders than adults, whilst visual searching found more adult snails and spiders than juveniles (sections 5.4.2, 6.4.3-4). Three snail species and three families were only found by suction, whilst all snail species observed *in situ* were sampled via suction (section 5.4.3, Fig. 5.6). Three spider species and two families were only observed in situ, whilst seven species and three families were only captured through suction (section 6.4.5). In addition, the individual species abundances of snails and spiders were differently affected by the sampling methods (see Fig. 5.6, Table 6.3). These results were shown to be related to (i) the body size of the specimens, with more small-bodied snails (below 15 mm maximum shell size) being found via suction than visual searching, and more large-bodied snails (above 15 mm maximum shell size) visually found than captured by suction (see sections 5.4.3 and 5.6.4) and (ii) the different strata sampled by the two techniques, as the visual searching surveyed the outer surface of the foliage, whilst the suction sampled the outer surface and within the foliage (see section 6.7.2). These results suggest a discrete complementarity of the two sampling methods as found in previous studies (see Scharff *et al.* 2003).

Visual searching is dependent on the ability and the experience of the observer. As a result, there is a risk of undercounting (even with animals moving at the slow-pace of snails). Additionally, this method is quite time-consuming. Conversely, suction sampling is independent of the skills of the user as long as samples are taken consistently, e.g. the same length of time and the same engine intensity per sample; in addition, suction devices sample an area rapidly. The limits and efficiency of the two sampling methods are further discussed in sections 5.6.4, 6.7.2 and 7.7.2. For an estimation of the snail and spider abundance and species richness, and of the snail species composition of green walls, and if time is a constraint, suction sampling was shown to be sufficient (sections 5.6.4, 6.7.2). However, to estimate the species composition of spiders, it would be advisable to use the suction device with an additional method that samples a different stratum. For the study of insect populations on living walls in public areas, suction sampling appears to be the most suitable method.

Animals were identified to the species level with the exception of insect groups which were categorised using the morphospecies approach (although the Chalcidoidea were identified to species). The implications of using morphospecies are discussed in section 7.7.2, and it is concluded that some taxonomic training prior using this method is required to achieve appropriate categorisation (see also Oliver & Beattie 1993; Barratt & Derraik 2003; Derraik & Early 2010).

8.3 THE INFLUENCE OF GREEN WALL DESIGN ON BIODIVERSITY

The use of urban GW by animals may depend on the city size and the proximity to semi-natural and rural areas but also on the levels of pollution, intensity of human activity or other factors (see Hennig & Ghazoul 2011). The results of the present work showed similar invertebrate abundances and richness in Birmingham and London for living walls, and between London and Stoke-on-Trent for green screens, suggesting that big cities may be homogenous in their physical and biological environments, at least in terms of the species studied and on the species that can use GW systems (McKinney 2006).

Focusing on GF and LW, the present research showed that the vegetation covering vertical surfaces is likely to be used by different animal groups. However, each GW system does have specific features that result in different species compositions. Therefore, it may be possible to target particular animal species or groups by manipulating the design of the GW (Baudry & Bunce 2001; Francis & Lorimer 2011).

8.3.1 Prior and after plant establishment

The animal species that colonise green walls may be different if the plant establishment results from a natural and slow process (e.g. masonry walls, hedges and green façades apart from green screens), or if the structure was installed artificially with plants already covering and/or rooted at different heights (as for green screens and living walls). Whether most animal species arrive with the GW system, or whether they colonise the habitat after the installation, is not precisely known. It is probably a combination of the two and may depend on the type of system. Modules with growing media may arrive on site with several invertebrate species already on them, especially if the plants have been pre-grown in the modules prior installation, whereas plants on felt-layers system are typically planted with most of the growing media removed from around their roots. The study of the new living wall showed significant increases of the abundances and richness of the different arthropod groups over the summer (see sections 6.6.3 and 7.6.3), suggesting an active colonisation. The differences in animal biodiversity evident between new LW and well-established LW suggests that dynamic processes, such as accumulation, succession and turn-over, are likely to happen over time modifying and changing their species richness, abundance and composition (sections 6.5.1, 6.6.1, 6.5.1, 7.6.1); similar processes can be expected on GW in general.

8.3.2 Importance of ecological guilds

The botanical composition of green wall may attract herbivores (mostly Hemiptera), pollinators (e.g. Diptera: Syrphidae, Hymenoptera: Apidae, Lepidoptera) and frugivores (e.g. birds) depending on the palatability of the foliage (Reader & Southwood 1981), the chemical defences of the plant species (Reader & Southwood 1981; Nykänen & Koricheva 2004), the diversity in shape and colour of flowers (Morawetz *et al.* 2013; Campbell *et al.* 2014) and the production of berries or other fruits (see Jacobs *et al.* 2010). As such, host plant identity was shown to be more important than host plant richness for invertebrate diversity, richness and abundance, depending on the animal groups (White 2013). The abundance and richness of saprophages (e.g. Diptera: Muscidae larva), detritivores (e.g. snails) and fungivores (e.g. Diptera: Mycetophilidae) may be higher on LWS where such species may more easily access the growing media such as in the case of the horizontal and angled plastic modules (section 7.7.4.1). Predators (e.g. birds, spiders, Coleoptera: Coccinellidae) and parasitoids (e.g. Hymenoptera: Ichneumonidae) might rely directly on the abundance and richness of the invertebrates, either the overall community or specific species, but they may also be affected by some of the GW characteristics: the structural diversity of the botanical composition (e.g. web-weavers, see sections 6.5.6, 6.7) or density of foliage as a protection against human disturbance (e.g. bird, see section 4.5.2).

The results of this study suggested the importance of investigating the local surroundings and the position of the wall before planning the wall design. Surrounding vegetation and especially woody features may be necessary for high colonisation of Coleoptera and Hemiptera (section 7.5.4-5). Traffic may alter the green wall wildlife by creating a physical barrier preventing dispersal (sections 6.5.7, 7.5.5) unless the green wall is physically connected to other green infrastructure components. Bird, hymenoptera and spiders may be lower in GW in busy pedestrian areas (sections 4.5.2, 6.5.7, 6.7.3.3, 7.5.5, 7.7.6).

8.3.3 The specificity of green screens

Green screens had a smaller animal population than other GF or LW. Their primary function is to act as green fencing, although they can also be used to trap particles along roads (Dunnett & Kingsbury 2008) and do have some biodiversity value. Conversely, other green façades and living walls may be designed to enhance animal biodiversity, especially living walls where diverse plant species could be selected to attract specific animal species. In addition to the botanical composition, the height (Berg *et al.* 2013; Campbell 2011), a dense foliage (Franzreb 1983; Lee *et al.* 2010) and the potential accessibility to bare surface (Loyola & Martins 2008) may enhance animal biodiversity, with varying effects depending on the system. Bird boxes, bat boxes and/or invertebrate boxes can also be incorporated in the structure (pers. obs.). However, as the animal biodiversity is enhanced, animals regarded as pests may colonise the wall as well. During the study, such groups including snails, Hemiptera: Aphididae (whiteflies) and Diptera: Cecidomyiidae (gall midges) were found on all type of LWS (angled and horizontal plant boxes, plant pots, rockwool units) and GF (deciduous and evergreen foliage, walls with monoculture or polyculture (either *Hedera sp.* or other species)). On living walls, which typically have high levels of maintenance, their presence resulted in the application of pesticide (e.g. against weevils) or active removal (e.g. snails). Whether the aim is to attract or to repulse different animal groups, the frequency and intensity of maintenance may affect the use of the wall by the overall wildlife, birds, mammals or invertebrates.

8.4 PLANNING AND PUBLIC POLICY GUIDANCE

The current and rapid socio-demographic, technological and environmental changes have important consequences for the development of cities. Studying them is important to inform decision-makers for sustainable development of the urban environment that benefit both urban dwellers and biodiversity (Niemelä 2014). An easy way to increase green spaces in the living environment.

The vertical dimension is an often forgotten aspect for greening the environment that has almost limitless potential. Green walls are one way of enhancing biodiversity in towns and cities, being easily retrofitted where intensive green landscaping may not be achievable. Modern cities have large areas of wall space, and even if not all are suitable for growing plants, the available space which could be readily converted to green walls is enormous (Johnston & Newton 2004).Traditionally, vegetation on vertical surfaces has been through the use of climbing plants, however living wall technology allows a much wider range of colourful herbaceous plants to be introduced to this dimension. As such, vertical greening systems can change the perception of a city, its scenery and ambiance. The incorporation of green walls in future building plans or as a retrofitted structure (as for example a certain percentage of the total façade) may contribute to an increase in the physical and physiological health of residents as has been shown for other green components.

In the context of water conservation, the development of green walls will not have a detrimental effect on human drinking water supply due to their ability to thrive with non-potable water (either recycled rainwater or grey/blackwater).

8.4.1 Green walls: horticultural or low-intervention systems?

Two opposing philosophies can be followed for GW systems. They may be seen as horticultural systems where invertebrate and plant communities are intensively managed. This approach will result in vegetated structures where, for instance, dead plants are not tolerated, and foliage and flowers are well presented. To the public, such installations may appear to have the attributes of a natural system. Conversely, green walls may be managed as low-intervention systems, with maintenance reduced to essential actions (e.g. irrigation, safety checks). Due to the less controlled nature of this approach, negative perceptions by customers and the general public of issues such as presence of dead material and bare surfaces may need to be countered with appropriate information awareness on their value.

These two approaches are found in the use of green walls between domestic and non-domestic uses. Businesses tend to use green walls, and especially living walls, for the “environmentally responsible” message it sends to potential and existing customers, recognising also the enhanced working environment it creates and their contribution to sustainability. Therefore, living walls are usually chosen for their aesthetic value and are intensively managed to ensure a constant appealing appearance. Homeowners, on the other hand, are likely to install cheaper, more easily created and easily maintained green façades as a functional way to green their environment and to create habitat for animals.

As these two viewpoints bring the question of management into focus, it is important to note that heavy management may be cost-effective for smaller patches (under 100 m²), whilst relying on natural processes might be more functional and practical on larger patches (Gaston *et al.* 2013).

8.4.2 Provision of ecosystem services and access

Unlike most other species, human populations obtain most of their ecosystem resources from sources that are distributed over a much larger area than the one occupied by the population itself (Gaston *et al.* 2013). One way of reducing this important ecological footprint, would be to use urban areas to supply their own ecosystem goods and services (Gaston *et al.* 2013). The provision of these ecosystem goods and services, through different green infrastructure components, will have to be evenly spread across the urban landscape, allowing every city-dweller to have access to it. Currently, it has been shown that the perception of levels of provision and the inequalities of their availability and access depend on the socio-economic and the age groups of the urban residents (Cohen *et al.* 2012, Niemelä 2014). As such, it is important to have a better understanding of how the views of local residents can better inform the planning and design process of urban green walls. Overall, the characteristics of the residential areas need to be considered in the planning and the management of green components.

8.4.3 The importance of considering green walls multi-functionality and interconnections

Typically, green walls are installed in a given environment for one purpose in particular (see sections 2.1), such as the improvement of the landscape aesthetic. However, they will have other impacts that are important and that need to be evaluated and included in the assessment of their effects. This consideration is already emerging as for example, when homeowners install living walls (usually in urban areas where space is a constraint), either through manufactured systems or DIY, it is usually with some kind of sustainability value in mind and as a new way to green their space (pers. obs.). However, currently the cost of most manufactured living walls makes them too expensive for domestic use and most small companies. Once their environmental values have been quantified and transferred into economic value, it is likely that their long-term effects will balance their initial cost. As such, they could be efficiently integrated into urban planning policies and building guidelines/regulations.

8.5 RECOMMENDATIONS FOR FURTHER RESEARCH

This section provides some recommendations for further research on the value of vertical greening systems for animal populations. As the work presented here preliminary findings of green wall animal ecology, more quantitative research is recommended:

- to investigate further the inclusion of green walls within green infrastructure components networks;
- to compare the varying values of different green wall systems with specific focus on
    - the materials of the panels,
    - the varieties of substrates, depth and moisture content;
- to study the influence of the vegetation cover with specific focus on
    - botanical composition,
    - plant structural complexity,
    - plant density;
- to give more insight on the influence of the surroundings;
- to investigate which animal species/guilds may use the wall exclusively and which species/guild may use the wall as part of the GW network

  According to Köhler *et al.* (1993), GF may be a suitable alternative living space for most invertebrates in urban areas, and when isolated, it can act as an exclusive habitat. For example, in Berlin the jewel beetles *Agrilus dreasofasciatus*, a Coleopteran species common in wine growing areas, was exclusively found on GF (Köhler *et al.* 1993). Generalist species are likely to colonise green walls more easily, as their needs will be more easily met (Adams & Lindsey 2009) than specialist species relying on special habitat requirement (see Fernandez-Juricic 2000; Lizée *et al.* 2011). However, by creating a new type of habitat, green walls may be offering resources that were not previously available in urban areas. Looking at the integration of green walls within the green infrastructure network, it would be of interest to identify which animal species could exclusively use green walls in dense human areas and which species may use the green walls as part of GI components.
- to consider how to enhance the use of LW by birds;

Bird populations fluctuate in response to factors such as habitat alteration (land-use changes, fragmentation, isolation, loss), active conservation schemes, climate change, human presence, etc. (e.g. Fernandez-Juricic *et al.* 2001; Devictor *et al.* 2008; Vickery *et al.* 2009; Evans *et al.* 2011; Lin *et al.* 2012; Suarez-Rubio *et al.* 2013). Most of the studies that have described the effect of urbanisation on animal species richness have focused on birds (McKinney 2008), although there are other studies on other groups such as bat (Threlfall *et al.* 2012) or invertebrates (e.g. Matteson & Langellotto 2010; Hennig & Ghazoul 2011). Although being a subject of interest in its own right, the status of British birds can be a useful indicator of the ecological state and even economic value of urban areas (e.g. Herrando *et al.* 2012; Lin *et al.* 2012; Hong *et al.* 2012), as such, their biodiversity has been shown to be related with the cost of housing (Farmer *et al.* 2011). Birds use green façades for feeding (fruits, invertebrates), nesting, mating and resting (pers. obs.) and could potentially use living walls. The vegetation on the wall may provide enough cover for the larger species (described as less tolerant to human presence, e.g. *Corvus brachyrhynchos* crow and *Sturnus vulgaris* starling (Fernandez-Juricic *et al.* 2001; Campbell 2011). Investigating how to design GW to enhance bird fauna could include among others factors, the identification of resources that can be provided by GW and how to optimise their delivery. It is likely that enhancing the value of living walls for birds will require specially designed living walls, mostly maintenance free or at least avoiding maintenance actions during specific time (e.g. nesting).

- to examine the potential presence of a height gradient (above 2 meter high)

Many grassland insects move up and down vegetation, not only in response to weather changes, but also at certain times of the day and night, with quite a proportion of active insects being airborne during the day (Southwood & Henderson 2000). On the other hand, some insect groups were shown to move at a specific height above grassland or forest canopy (Boivin & Stewart 1984; Blackmer *et al.* 2008; Byers 2009). Similar variation on heights may be expected on the walls. In addition, environmental conditions may be different at different heights: the top of the wall may suffer harsher weather-related conditions (e.g. greater wind, rainfall interception, see Hang *et al.* 2013), whereas the bottom may experience greater levels of air pollution, vehicle and pedestrian traffics. It could be interesting to investigate if there is a gradient of utilisation, i.e. if animal utilisation of the wall (for feeding, protection, nesting, etc.) varies with the height, or if there is an optimal height where most animals settle.

- to explore the influence of aspect and shade

The aspect of the wall was shown to have no effect on animal abundance and richness (see sections 6.4.7, 6.5.6, 7.4.5, 7.5.4). However, this factor and the effect of shade on the wall on the invertebrate activity could be more thoroughly investigated.

More experiments are recommended and may be designed to study the impact of these factors individually. Studies of the aggregated effects may also be of interest to investigate how to design an optimal vertical greening system to enhance wildlife in urban areas.

8.6 CONCLUSION

In busy environments like cities, green walls allow greenery without competing with space people can use. Greening pedestrian and public areas make green features more accessible to everyone than covering a roof top with plants. Thus, green walls have a substantial role to play in the enhancement of biodiversity in urban areas. They may be used as animal habitats, offering valuable resources in the urban environment. In areas with very little green spaces, they may provide the only available source of food, shelter, egg laying, etc. in the local area (Köhler *et al.* 1993). The approaches of 'restoration', 'reconciliation' or 'recombinant' ecology (see Rosenzweig 2003; Rosenzweig 2004; Hinchliffe *et al.* 2005), raise the question whether green walls should be designed to replicate natural or semi-natural habitats or whether they should be used as a way to create novel assemblages that are not seen in nature. Because cities are by definition not 'natural', it is, perhaps, less important to try to replicate 'natural systems', and more relevant that the green features incorporated in the urban fabric host varied and functional assemblages of species. In that respect, the degree of maintenance will play a substantial role by altering the vegetation structure, density, and composition of the green wall. As the vertical assemblages of plants found on living walls are not commonly found in nature, this gives the opportunity to create a complete new ecosystem able to thrive and develop in cities. Recreating and supplementing threatened habitats within a city setting offers new avenues for conservation. Working on green walls in urban settings is an emerging area of ecology; exploring the functionalities and the possibilities of green walls, and especially living walls, should not be constrained by conventional conservation paradigms.

THESIS'S MAIN FINDINGS SUMMARY

The principal aim of this doctoral research was to obtain insight into the potential value of green walls for animal biodiversity.

The sampling techniques (i.e. visual searching for birds, snails and spiders, suction sampling for shelled molluscs, spiders and insects, and categorisation of spider webs) were carried out between 0 and 2 meters high. Animals were identified to species or morphospecies levels. Twenty-nine green façades were surveyed in three occasions per season from July to March in Stoke-on-Trent and Newcastle-under-Lyme; twenty-two living walls (6 different systems) and four green screens were surveyed in four occasions during July and September in The Greater London Area and Birmingham.

Additionally to Table 8.1 and Figure 8.1 (which give the influences of each investigated factors and the influences of sampling methods respectively), the main findings can be summarised as followed:

- A similar invertebrate fauna was found on green walls of different big cities.
- Bird, snails, spiders, and insects were found on all living wall systems whatever the height of installation of the wall from the ground.
- In total, 9 species of birds, 13 species of snails, 33 species of spiders and over 2600 morphospecies of insect were found on green façades and living walls.
- Birds were more present in residential areas with green walls than in residential areas without green walls.
- No snails were found of green screens; whilst spiders and insects were found on them.
- Spider species were mostly generalist and foliage spiders, some of them indicative of humid habitats.
- Diptera, Hemiptera and Hymenoptera were the more abundant and species-rich orders on green walls.
- Pests (e.g. gall midges, whiteflies) and their predators (e.g. ladybug) or parasitoids (e.g. solitary wasps) were found on all the different types of walls.
- The proportionally large abundance of Psocoptera is an indicator of the important presence of organic material due to the decaying vegetation within green walls.
- Comparison of family and species composition between GF and LW revealed that:
    - 28 insect families were only found on green façades (of which 2 Coleoptera, 13 Diptera, 7 Hemiptera and 4 Hymenoptera) and 14 families were only found on living walls (of which 3 Coleoptera, 3 Diptera, 1 Hemiptera, and 4 Hymenoptera) (Table 7.22).
    - only eight spider families (57.1%) and seven genera (23.3%) have been found in both systems (see Table 6.15 for further details). Ten spider genera were

exclusively found on green façades, ten others were exclusively found on living walls.

These differences suggest little overlap in the species composition of GF and LW: this is probably related to their quite different structural characteristics and resulting environmental conditions. As such green façades (green screens included) and living walls need to be considered as separate ecosystems.

- The influence of the sampling techniques in the evaluation of the snail and the spider populations on green walls are summarised in Figure 8.1.
- Insect total abundance and total richness were not affected by the wall's characteristics (e.g. age) or the wall surroundings (e.g. pedestrian traffic volume) but the insect orders were affected differently (see Table 8.1 for more details).
- The type of LW system had no effect on total insect abundance or richness; however, it had different impacts on insect orders (see below in decreasing order - for details see section 7.5.2) and on spider fauna:
    - Diptera were more abundant and rich in horizontal plant boxes and the plant pot system than in the other systems.
    - Hemiptera were more abundant and rich in rockwool units than in the other systems.
    - Coleoptera and Hymenoptera abundance and richness were not affected by the different LW systems.
    - Spiders were more abundant and rich on angled plastic modules and rockwool units than on the other systems.
- Although most of the walls were planted up with 'mature' plants, the age of the wall was positively related with spider abundance and richness, negatively related with Diptera and not related with the other insect orders.
- The surface area of wall vegetation was positively related to Coleoptera and Hemiptera and not related with the other insect orders or the spider fauna.
- The plant density and richness were positively related with spider fauna (apart from orb-weavers), negatively related with Diptera and not related with the other orders.
- Hemiptera were more species-rich in the summer than the autumn and Dipteran richness was higher in the autumn than the summer; whilst the other insect orders were not affected by seasonality. Spider abundance was greater in the summer than in the autumn and species composition varied between seasons.
- Vehicle traffic volume was negatively related to Coleopteran abundance but not related with the other insect orders or spider populations (maybe due to a distance of at least 4 m between LW and road which might be enough to create an isolated habitat).

- Human activity (pedestrian traffic volume, maintenance interventions and frequency) was negatively related to spider fauna (apart from orb-weaver abundance) and Hymenopteran abundance but was not related to the other insect orders.
- Surrounding vegetation was positively related with Coleoptera and Hemiptera, but not related with the other insect orders or spider populations (which suggest that the latter find the extent of the resources they need within the green walls).

Over all, green walls characteristics (especially plant diversity, plant density and green wall age) influencend insect taxa more than the type of LWS or the surroundings. In addition, insect taxa were responding differently, and sometimes in a reverse sense to these variables. As such, according to the results of the present study, no LWS can be advocate as best for animal populations; however, their design and maintenance frequency will play a role in their animal populations.

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APPENDIX

APPENDIX

Appendix 1. Results of the Pilot Study carried out in the summer of 2010

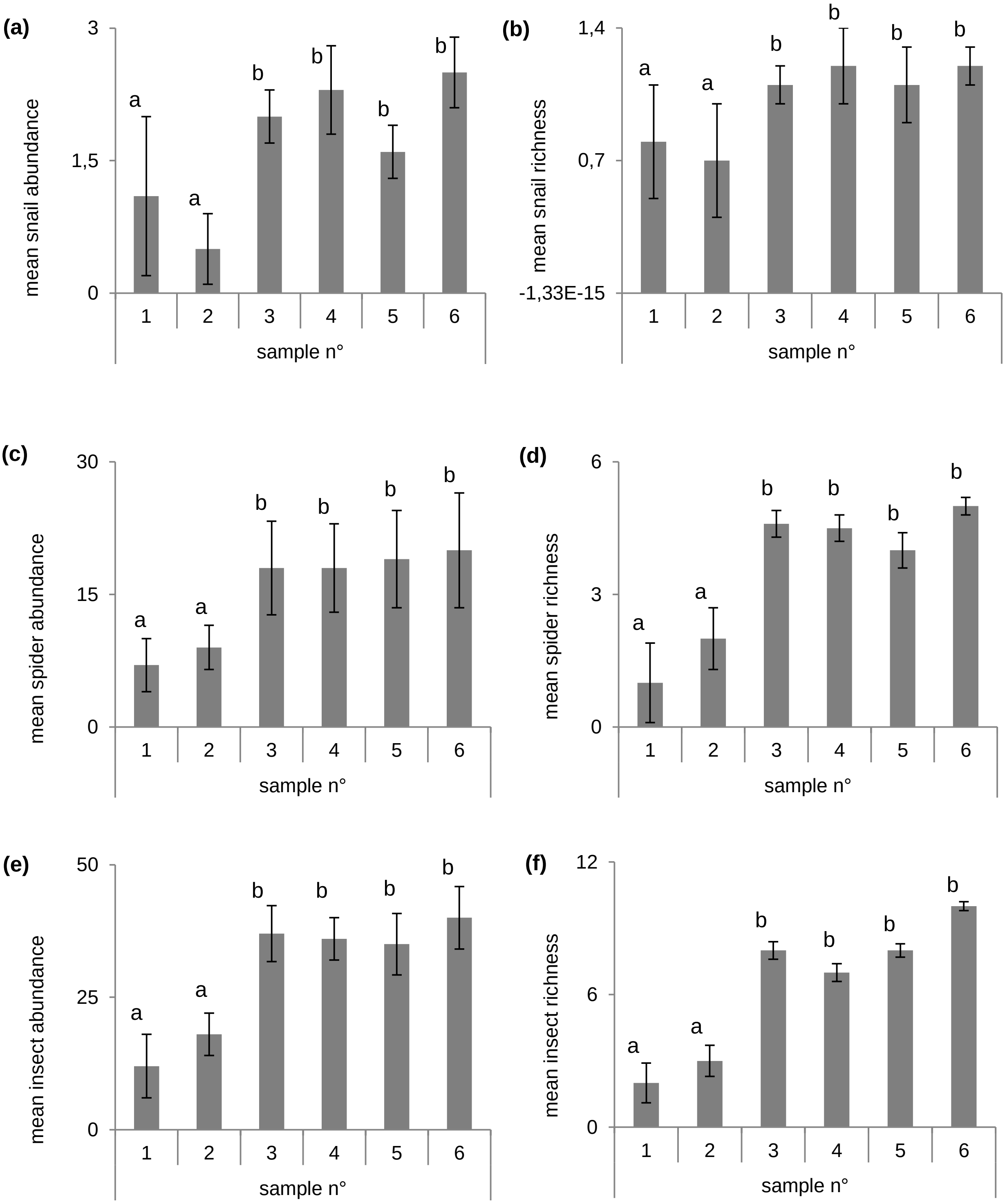

Figure A. Mean abundance and species richness of snails (a, b), spiders (c, d), insects (e, f) over time using suction sampling (±1SE)

Different letters indicate significant differences; see Table A for further details. Invertebrate surveys using suction sampling on green façades (n=10), in the summer of 2010, Staffordshire, UK.

Table A. Comparative analysis of invertebrate abundance and species richness over time using suction sampling.

sample n°		invertebrate abundance						invertebrate species richness					
		snail (a)		spider (c)		insect (e)		snail (b)		spider (d)		insect (f)	
		z value	*p* value	z value	*p* value	z value	*p* value	z value	*p* value	z value	*p* value	z value	*p* value
1 vs.	2	-0.46	0.646	-0.99	0.379	-0.83	0.447	-0.27	0.794	-4.28	**<0.001**	-4.29	**<0.001**
	3	-2.43	**0.015**	-5.56	**<0.001**	-4.99	**<0.001**	-2.37	**0.020**	-3.99	**<0.001**	-4.87	**<0.001**
	4	-2.88	**0.014**	-5.36	**<0.001**	-6.24	**<0.001**	-2.29	**0.018**	-4.48	**<0.001**	-4.98	**<0.001**
	5	-2.40	**0.012**	-4.79	**<0.001**	-5.05	**<0.001**	-2.40	**0.013**	-4.30	**<0.001**	-4.48	**<0.001**
	6	-2.50	**0.013**	-4.99	**<0.001**	-6.19	**<0.001**	-3.12	**0.07**	-4.37	**<0.001**	-4.50	**<0.001**
2 vs.	3	-3.86	**<0.001**	-4.76	**<0.001**	-4.48	**<0.001**	-2.46	**0.018**	-4.35	**<0.001**	-4.87	**<0.001**
	4	-2.81	**<0.001**	-4.27	**<0.001**	-4.29	**<0.001**	-2.75	**0.012**	-4.21	**<0.001**	-4.34	**<0.001**
	5	-3.20	**0.002**	-3.86	**<0.001**	-4.23	**<0.001**	-2.55	**0.015**	-2.99	**<0.001**	-4.46	**<0.001**
	6	-3.87	**<0.001**	-5.00	**<0.001**	-4.69	**<0.001**	-2.99	**0.002**	-4.65	**<0.001**	-4.57	**<0.001**
3 vs.	4	-1.80	0.514	-1.67	0.618	-0.27	0.790	-1.50	0.132	-0.83	0.404	-1.22	0.221
	5	-0.90	0.366	-0.75	0.460	-0.86	0.405	-1.71	0.087	-0.99	0.321	-1.21	0.220
	6	-1.66	0.298	-0.58	0.552	-0.38	0.645	-1.13	0.257	-0.47	0.645	-1.17	0.241
4 vs.	5	-1.75	0.380	-0.60	0.547	-0.60	0.547	-1.34	0.180	-1.18	0.453	-0.20	0.839
	6	-0.76	0.444	-0.57	0.537	-1.03	0.305	-1.57	0.160	-1.34	0.380	-0.85	0.403
5 vs.	6	-1.95	0.390	-0.43	0.632	-0.85	0.403	-1.75	0.137	-1.07	0.474	-0.83	0.485

Statistical results referring to Figure A. Data report post-hoc test (WT) following a Friedman test: snail abundance: $\chi^2_{(5)}$= 9.40, p=0.024, species richness: $\chi^2_{(5)}$= 8.29, p=0.040; spider abundance: $\chi^2_{(5)}$= 18.27, p<0.001, species richness: $\chi^2_{(5)}$= 19.39, p<0.001; insect abundance: $\chi^2_{(5)}$= 29.35, p<0.001, species richness: $\chi^2_{(5)}$= 38.21, p<0.001. Green façades (n=10), summer 2010, Staffordshire, UK.
Non-parametric tests were conducted as the data did not meet the assumptions of normality, even after attempts of transformations. NOTE: results are display as means on graphs but tests are run on the medians, hence the apparent similarity between some of the groups.

Results:

Sampling a green façade (n=10) in three occasions achieved the same estimate of mean abundance and species richness of snails, spiders and insects as four, five and six samples.

Appendix 2. Potential plants for living walls and their characteristics

Note: selected plants are usually evergreen and perennial although some can be herbaceous, and annual or biannual.

Plant name (examples of species and 'cultivar')	plant type	shade tolerant	growth habit
Abutilon sp. (*A. megapotamicum*)	foliage	outdoor	spreading, drooping, creeping
Acaena sp. (*A. mocrophylla)*	foliage	outdoor	covering
Achilea sp. (*A. millefolium, mollis*)	flowering (15-20 flowring stem)	can be shade tolerant	spreading, drooping
Acorus sp. (*A. gramineus* 'Ogon')	grass-like		
Adiantum sp. (*A. bronze* 'venus', *caudatum, fragrans, luthi, microphyllum*)	fern	in or outdoor	spreading, drooping
Aeschynanthus sp.	flowering		drooping bush
Aethionema sp.	foliage	outdoor	bushy
Aglaonema sp. (‘Crete’, ‘First diamond’)	foliage		
Agrostis sp.	grass-like	outdoor	drooping
Ajuga sp. (*A. reptans* 'Black Scallop')	flowering	outdoor, sunny area	covering
Allocasia sp. (‘dwarf amazonica’, 'bambino')	foliage	indoor	
Anacyclus sp.	foliage	outdoor	covering
Angraecum sp.	orchids	indoor	upright
Anoectochilus sp. (*A. roxburghii*)	foliage	indoor	
Anthurium sp. ('cristal', 'jungle bush')	flowering	indoor	
Aptenia sp.	foliage	outdoor	covering
Arabis sp. ('old gold')	flowering	outdoor	covering
Aralia sieboldii / Fatsia japonica	flowering	indoor	
Armeria sp. (*A. maritime*)	foliage	outdoor	
Asparagus sp. (*A. falcatus, plumosus, pyramidalis, sprengeri*)	fern	in or outdoor	spreading, drooping

(continued)

(continued)

Plant name (examples of species and 'cultivar')	plant type	shade tolerant	growth habit
Asplenium sp. (*A. nidus, scolopendrium, scolopendrium* 'Angustifolia', *trochomenes*)	fern	shade tolerant, in or outdoor	spreading, drooping
Aubrieta sp. ('Double Pink')	flowering		
Azorella sp. (*A. trifurcate)*	foliage	outdoor	covering
Begonia sp. (*B. bowerae, grandiflora, rex*)	flowering	shade tolerant , in or outdoor	drooping
Berberis sp. (*B. thunb* 'Atropurpurea Nana')	shrub (interesting foliage and dark red fruit)		
Bergenia sp. (*B. cordiflora,* 'ouverture')	flowering	shade tolerant	covering
Billbergia sp.	foliage	indoor	
Blechnum sp. (*B. spicant*)	fern	shade tolerant, in or outdoor	spreading, drooping
Brunnera sp. (*B. macrophylla*)	flowering	shade tolerant	
Buxus sp. (*B. sempervirens*)	woody		
Calathea sp. (*C. makoyana, royale, rufibarba*)	foliage	indoor	
Camelia sp.	woody		
Campanula sp. (*C. poscharskyana* 'Lisduggan')	flowering (stary lavendar-pink flowers)	sunny area, outdoor	clumb-forming, spreading
Carex sp. (*C. comans* 'Bronze Form', *humilis, morrowii, ornithopoda, oshimensis, testacea*)	grass-like	can be shade tolerant	
Ceropegia sp. (*C. woodii*)	foliage	indoor	drooping, climbing
Chamaedorea sp.	woody	indoor	bushy
Chiastophyllum sp. (*C. oppositifolium* 'Jim´s Pride')	succulent		
Chlorophytum sp. (*C. comosum* 'Ocean', *laxum*)	foliage	indoor	
Choisya sp. (*C. ternata* 'sundance')	woody		
Cinta sp. (*C. comosum* 'variegated')	grass-like		
Cissus sp. (*C. striata*)	climbers	in or outdoor	climbing

(continued)

(continued)

Plant name (examples of species and 'cultivar')	plant type	shade tolerant	growth habit
Cistus sp.	flowering (white to purple and dark pink flowers)	outdoor	bushy
Clematis sp. (*C. montana*)	climbers		climbing
Climbing Rose (e.g. *Rosae* 'blairii number two')	climbers		climbing
Codiaeum variegatum	woody		
Cordyline sp. (*C. glauca, mambo, tango*)	woody	indoor	upright
Cornus sp. (*C. canadensis*)	flowering	shade tolerant	
Cotonéaster sp. (*C. procumbens*)	woody		
Crotons sp.	foliage	indoor	
Cryptanthus sp. (*C. fosterianus*)	foliage	indoor	
Ctenanthe sp.	foliage	indoor	
Cyrtomium sp. (*C. falcatum, fortunei*)	fern	in or outdoor	spreading, drooping
Darmera sp. (*D. peltata*)	flowering	only sunny side	
Davallia sp. (*D. marieslii*)	fern	indoor	spreading, drooping
Delosperma sp.	foliage	outdoor	covering
Dianthus sp. (*D. deltoïdes, rubin*)	flowering	outdoor	covering
Didymochlaena sp.	fern	indoor	spreading, drooping
Dieffenbachia sp. (*D. camilla, compacta, veerle*)	foliage	indoor	
Dracaena sp. (*D. compacta*)	foliage	indoor	
Dryopteris sp. (*D. erythrosora*)	fern	outdoor	spreading, drooping
Duchesnea sp.	foliage	outdoor	covering
Eoimedium sp.	foliage	outdoor	bushy
Epimedium sp. (*E. rubrum*)	flowering	shade tolerant	

(continued)

(continued)

Plant name (examples of species and 'cultivar')	plant type	shade tolerant	growth habit
Epipremnum sp. (*E. aureum 'pothos'*)	woody	indoor	creeping
Erigeron sp. (*E. karvinskianus*)	flowering	outdoor	
Eriogonum sp. (*E. umbellatum*)	flowering (diverse colours)	outdoor	bushy, covering
Eruca sativa (i.e. salad rocket)	herb, vegetable or fruit plants		
Erysimum sp. ('Bowles Mauve')	woody		
Escallonia sp. (*E. macrantha*)	woody		
Euonymus sp. (*E. fortunei* 'Harlequin', 'Darts Blanket', 'Emerald Gaiety', 'Emerald n' Gold')	woody (green/yellow foliage; black berry)	shade tolerant	
Euphorbia sp. (*E. amygdaloides, characias* 'Humpty dumpty', *myrsinites*)	woody (dark green slightly hairy foliage)	outdoor	ground-cover or bushy
Fallopia sp. (*F. baldschuanica, japonica*)	climbers		climbing
Fatsia sp. (*F. japonica*)	woody	in or outdoor	upright
Festuca sp. (*F. gautieri, glauca*)	grass-like	sun	
Ficus sp. (*F. pumila, repens* 'sunny')	woody	indoor	creeping
Fittonia sp. (*F. janita,* 'forest flame')	foliage	indoor	
Fragaria vesca (i.e. strawberry plant)	herb, vegetable or fruit plants	only sunny side	
Geranium sp. (*G. cantabrigiense* 'Cambridge')	flowering	shade tolerant	
Glechoma sp.	foliage	outdoor	covering
Guzmania sp. (*G. magnifica*)	flowering	in or outdoor	
Gynura sp.	foliage	indoor	
Hatiora sp.	foliage	indoor	drooping
Hedera (*H. canariensis, helix* 'Hibernica', 'Glacier', 'Goldchild', 'Green Ripple', 'White Ripple', 'Woerner')	climbers	in or outdoor	climbing
Helianthemum sp. ('Golden Queen')	flowering	only sunny side	

(continued)

(continued)

Plant name (examples of species and 'cultivar')	plant type	shade tolerant	growth habit
Helleborus sp. (*H. nigra*)	flowering (green flowers)		
Helxine sp.	foliage	indoor	
Hemerocallis sp. (*H. hybriden*)	flowering	shade tolerant	
Heuchera sp. ('americana', 'Jade´s Gloss', 'marmalade', 'Midnight Rose', 'Palace Purple', 'Paris')	flowering (10-20 flowering stem, dark foliage)	shade tolerant	
Hortensia sp.	woody		
Hosta sp. (*H. hybride* 'Golden Tiara')	flowering	shade tolerant	
Hoya sp.	woody	indoor	drooping
Humulus sp. (*H. lupulus*)	climbers		climbing
Hypericum sp. (*H. calysinum*)	woody		
Hypoestes sp.	foliage	indoor	bushy
Iberis sp.	flowering		
Ilex sp. (*I. cassine, creneta* 'Convexa')	woody	shade tolerant	
Iris sp. (*I. foetedissima, japonica*)	flowering	outdoor	
Jasmine sp.	climbers		climbing
Juniperis sp. (*J. horizontalis*)	woody	shade tolerant	
Kerria sp. (*K. japonica*)	flowering	shade tolerant	
Koeleria sp. (*K. glauca*)	climbers		climbing
Lamium sp. (*L. maculatum* 'White Nancy')	flowering		
Lavandula sp. (*L. augustifolia* 'munstead')	flowering	outdoor	bushy
Linum sp.	flowering	outdoor	
Liriope sp. (*L. muscari* 'Silver sceptre')	grass-like		
Lithodora sp. (*L. diffusa* 'Heavenly Blue')	woody		

(continued)

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Plant name (examples of species and 'cultivar') (continued)	**plant type**	**shade tolerant**	**growth habit**
Lonicera sp. (*L. nitida* 'Maigrun', *periclymenum*)	climbers	shade tolerant, in or outdoor	climbing
Ludisia sp.	orchids	indoor	spreading, creeping
Mahonia aquifolium	woody	shade tolerant	
Maranta sp. (*M. amabilis, eucpmeura* ' Erythrofylla', *kerckhoviana, leuconeura, tricolor*)	woody	indoor	spreading
Mazus sp. (*M. reptans* 'Albus')	flowering	shade tolerant	
Mentha sp. (*M. spicata, requenii*) (i.e. mint)	herb, vegetable or fruit plants		
Microlepia sp.	fern	indoor	spreading, drooping
Miltonia sp.	orchids	indoor	
Nepenthes sp.	foliage	indoor	
Nepeta sp. (*N. faassenii* 'Senior')	flowering		
Nephrolepis sp. (*N. cordata, exaltata, sonata*)	fern	indoor	spreading, drooping
Nidularium sp.	foliage	indoor	
Oncidium sp.	orchids	indoor	upright
Ophiopogon sp. (O. japonica, niger)	grass-like (lilac flowers, purplish-dark foliage)	in or outdoor	club-forming
Pachysandra sp. (*P. terminalis*)	flowering	shade tolerant, outdoor	covering
Paphiopedilum sp.	orchids	indoor	upright
Paronychia sp.	foliage	outdoor	covering
Parthenocissus sp. (*P. quinquefolia, tricuspidata*)	climbers		climbing
Passiflora sp.	climbers		climbing
Pellaea sp. (*P. cordata, falcata, rotundifolia*)	fern	indoor	spreading, drooping
Penstemon sp. ('Garnet')	flowering	shade tolerant	
Peperomia sp. (*P. argyreia, prostata, rotundifolia, serpens, variegata, yelli*)	foliage	in or outdoor	

(continued)

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Plant name (examples of species and 'cultivar')	plant type	shade tolerant	growth habit
Phaleaenopsis sp.	orchids	indoor	dropping
Philodendron sp. ('Congo Green', 'Imperial Green', *P. monstera, scadens, selloum, xanadou*)	foliage	indoor	drooping, climbing
Phlebodium sp. (*P. aureum*)	foliage	indoor	
Phlox sp. (*P. borealis, douglasii, subutala* 'Emerald Cushion')	flowering	outdoor	covering
Photinia sp. (*P.* 'red robin')	woody		
Phylliti sp. (*P. scolopendrium 'undulata'*)	fern	in or outdoor	spreading, drooping
Physocarpus sp. (*P. opulifolius*)	woody	shade tolerant	
Pilea sp. (*P. cadierei, microphylla, norfolk*)	foliage	indoor	upright
Pinus sp. (*P. mugo mugo*)	woody	only sunny side	
Platycerium sp.	fern	indoor	spreading, drooping
Pleomele sp. ('song of india')	woody	indoor	upright
Polygonatum sp. (*P. multiflorum*)	flowering	shade tolerant	
Polypodium sp. (*P. vulgare*)	fern	in or outdoor	spreading, drooping
Polystichum sp. (*P. munitum, polyblepharum, setiferum* 'dahlem' or 'herrenhaouden')	fern	shade tolerant, in or outdoor	spreading, drooping
Potentilla sp. (*P. fruticosa* 'Abbotswood')	woody	shade tolerant	covering
Prunis sp. (*P. 'otto luyken'*)	woody		
Pteris sp. (*P. argyraea , cretica* 'mayi' or 'wimsetii', *erythrosora, evergemiensis, faurei, ouvrardi*)	fern	indoor	spreading, drooping
Pycnanthemum sp. (i.e. mountain mint)	herb, vegetable or fruit plants		
Rhipsalis sp.	foliage	indoor	drooping
Roulia sp.	foliage	outdoor	covering
Rudbeckia sp. (*R. fulgida* 'Goldsturm')	flowering	only sunny side	

(continued)

(continued)

Plant name (examples of species and 'cultivar')	plant type	shade tolerant	growth habit
Sagina sp.	flowering	outdoor	covering
Salvia sp. (*S. nemorosa, officinalis*) (i.e. mint)	herb, vegetable or fruit plants	only sunny side	bushy
Sarcococca sp.	woody		
Saxigraga sp. (*S. umbrosa, urbrium*)	foliage	outdoor	covering
Schefflera sp. (*S. luseana*)	woody	indoor	upright
Sedum sp. (*S. acre, album, kamchaticum, spurium*)	succulent	outdoor	covering
Selaginella sp.	foliage	indoor	covering
Solanum lycopersicum (i.e. tomato plant)	herb, vegetable or fruit plants		
Soleirolia sp. (*S. soleirolii*)	flowering		
Spathiphyllum sp. (*S. wallisii*)	flowering	indoor	upright
Spiraea sp. (*S. japonica* 'Goldflame')	woody	only sunny side	
Stachys sp. (*S. byz* 'Silver Carpet')	foliage		
Sygonium sp. (*S. andrea*)	foliage	indoor	drooping, climbing
Symphoricarpus sp. (*S. chenaultii* 'Hancock')	woody	only sunny side	
Syngonium sp. (*S. brenda, neon, wanda,* 'white butterfly')	foliage	indoor	drooping, climbing
Tellima sp. (*T. grandiflora*)	flowering	outdoor	
Teucrium sp. (*T. lucidrys*)	woody		
Thymus sp. (*T. serphyllum*)	herb, vegetable or fruit plants	shade tolerant	covering
Tiarella sp. (*T. cordifolia, wherryi*)	flowering (15-20cm tall flowering stem; foliage dark green)	shade tolerant	ground-cover
Tillandsia sp.	foliage	indoor	
Tolmiea sp.	foliage	outdoor	covering
Tradescantia sp.	foliage	indoor	covering, drooping, climbing

(continued)

(continued)

Plant name (examples of species and 'cultivar')	plant type	shade tolerant	growth habit
Tunica sp.	foliage	outdoor	covering
Veronica sp. (*V. repens, waterperry*)	flowering	shade tolerant	
Vinca sp. (*V. minor*)	flowering	shade tolerant	covering
Waldsteinia sp. (*W. ternata*)	flowering	only sunny side	
Wisteria sp.	climbers		climbing

Adapted from Dunnett & Kingsbury 2008 and Blanc 2008 (see full references in references section).

Appendix 3. Potential plants for green façades and their characteristics

Note: Weight : very light < 10kg/m²< light <15 kg/m²<medium<20kg/m²<heavy<25kg.m²

Family	Specie examples (common name)	Height x profile (max in cm)	Hardiness zone	Foliage	Flower colour (season)	Fruit	Origin	Aspect	Climbing mechanism	Vigor	Max weight (kg/m²)	Min height x optimum width of support (m)	Distance from wall (cm)
Acanth a-ceae	*Thunbergia grandiflora* (bengal vine)	600x60	10	elliptic	blue-mauve trumpet (summer to autumn)	-	northern India	sun, shelter	twining	strong	15	2x2	8
Actinidiaceae	*Actinidia arguta* (Siberian gooseberry)	900x60	4	yellow (autumn)	white (early summer)	yellow-green	eastern Asia	light shade to sun	twining	strong	20	5x3	15
	Actinidia deliciosa (Chinese gooseberry)	1200x90	7	-	cream-colour (early summer)	kiwi of commerce	China	full sun	twining	very strong	25	6x4	15
	Actinidia kolomikta	600x90	4	white and pink splashes	white (early summer)	yellow-green	eastern Asia	full sun, dislikes exposure	twining	medium	20	3x2	8
Apocyna-ceae	*Trachelospermum jasminoides*	900x30	8	evergreen	cream-color (summer)	-	eastern Asia	light shade to sun, shelter	twining	medium	15	4x2	5
Araliaceae	*Fatshedera lizei*	6x4 (profile) x90	7	dark green	-	-	garden origin	shade, dislikes full sun	rambler	medium	15	3x2	10
	Hedera helix (English ivy)	1000x30	4	dark green	green (autumn)	black, in spherical clusters	Europe, western Asia	sun or shade	aerial roots	strong	-	-	-
Aristolo-chaceae	*Aristolochia macrophylla* (Dutchman's pipe)	1000x60	7	-	mottled (summer)	-	eastern North America	light shade	twining	strong	15	8x3	10

(continued)

(continued)

Family	Specie examples (common name)	Height x profile (max in cm)	Hardiness zone	Foliage	Flower colour (season)	Fruit	Origin	Aspect	Climbing mechanism	Vigor	Max weight (kg/m²)	Min height x optimum width of support (m)	Distance from wall (cm)
Asclepiada-ceae	*Araujia sericifera* (cruel plant)	1000x60	9	evergreen	white (summer)	-	south America	light shade to sun	twining	medium	15	5x-	8
	Periploca graeca (silk vine)	900	6	ovate glossy	purple-brown, greenish (summer)	pods open silky tassels	south-eastern Europe, western Asia	sun	twining	strong	-	8x3	8
Bignoniaceae	*Bignonia capreolata* (trumpet flower, cross vine)	2000x90	10	evergreen	orange-red (summer)	flat	south-eastern US	light shade to sun	leaf tendrils	very strong	20	6x-	10
	Campsis radicans (trumpet vine)	1000x90	4	yellow in autumn	trumpet-shaped, orange-red (late summer to autumn)	-	China	full sun vital	aerial roots	strong	15	6x4	15
	Pyrostegia venusta (flame vine)	2500x90	10	evergreen	bright orange trumpets (summer)	-	southern SA	sun	twining stems and tendrils	strong	15	10x-	10
Cannabi-naceae	*Humulus lupulus* (hop)	700x90	3	light green	-	green-ish, papery, decorative	northern Hemi-sphere	light shade to sun	twining	very strong	10	6x2	5
Caprifo-liaceae	*Lonicera japonica* (evergreen honeysuckle)	1000x90	4	ovate	white (summer)	-	Japan	light shade to sun	twining	strong	10	5x3	5

(continued)

(continued)

Family	Specie examples (common name)	Height x profile (max in cm)	Hardiness zone	Foliage	Flower colour (season)	Fruit	Origin	Aspect	Climbing mechanism	Vigor	Max weight (kg/m²)	Min height x optimum width of support (m)	Distance from wall (cm)
Caprifoliaceae (continued)	*Lonicera periclymenum* (common honeysuckle)	700x60	4	glaucus	yellowish white (summer)	red berries	Europe, Mediter-ranean	light shade to sun	twining	medium	10	4x2	5
	Lonicera tragophylla	1200x60	6	long ovate	yellowish orange (summer)	red berries	central China	shade or sun	twining	medium	10	6x3	5
Celastraceae	*Celastrus scandens* (American bittersweet)	1000x120	2	clear yellow in autumn	small yellow-green (summer)	bright orange seeds	eastern North America	light shade to sun	twining	strong	15	7x2	15
	Eunymus fortunei	500x60	5	evergreen dark, green, silver or gold	-	white fruit, orange	eastern Asia	light shade to sun	aerial roots	medium	20 -25	4x2	10
Convol-vulaceae	*Ipomea hederacea* (morning glory)	500x30	8	3-lobed	blue (summer)	-	Japan	sun	twining	strong	10	2x2	5
Faba-ceae	*Wisteria Sinensis* (wisteria)	3000x120	5	pinnate, pale (spring)	blue-mauve trumpet (early summer)	flattened beanlike pods	eastern Asia	sun, shelter	twining	very strong	15	15x3	15
Hydrangeceae	*Decumaria barbara*	900x60	8	evergreen	white (summer)	-	south-eastern US	light shade to sun	aerial roots	medium	15	4x2	10
	Hydrangea petiolaris	1500x90	5		cream-colour (mid-summer)	-	far East	semi-shade to shade	aerial roots	medium	15	4x5	10
	Schizophragma hydrangeoides	1200x60	6	dark oval	hydrangea-like (early summer)	-	Japan	light shade, or sun	aerial roots	medium	15	4x5	10

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Family	Specie examples (common name)	Height x profile (max in cm)	Hardiness zone	Foliage	Flower colour (season)	Fruit	Origin	Aspect	Climbing mechanism	Vigor	Max weight (kg/m²)	Min height x optimum width of support (m)	Distance from wall (cm)
Lardizabalaceae	*Akebia quinata* (vhocolate Vine, five-leaf Akebia)	1000x60	5	five-lobed leaves	spicy-scented maroon (early spring)	violet, sausage-shaped	eastern Asia	very light shade	twining	strong	15	7x2	10
	Hollboellia coriacea	700x60	7	evergreen	green-white, pinkish (spring)	-	central China	sun and shelter	twining	strong	15	3x-	10
	Staunonia hexaphylla	1000x30	8	evergreen	violet-flushed white (spring)	drak greenish	eastern Asia	sun, shelter	twining	strong	15	5x-	10
	Sinofranchetia chinensis	1500x60	6	bluish-green	-	pale purple, grapelike	China	light shade	twining	strong	15	8x-	10
Menisperma-ceae	*Cocculus carolinus* (Carolina moonseed)	500	7	heart-shaped	white (summer)	red fruits in clusters	south-eastern US	light shade to sun	twining	-	-	3x-	10
	Menispermum canadense (Canada moonseed)	500	5	ovate	-	glossy black	eastern North America	sun	twining	strong	10	4x2	5
Mora-ceae	*Ficus pumilla* (climbing fig, creeping fig)	400x15	9	dark green	-	-	eastern Asia	light shade	aerial roots	medium	10	-	-
Nyctagi-naceae	*Bougainville spectabilis, glabra* (bougainvillea)	800x90	10	evergreen	small, brilliantly colourful bracts climate dependent	-	Brazil	sun	thorns	strong	20	4x4	15

Olea-ceae	*Jasminum officianale* (common jasmine)	1200x120	7	small pinnate	white (late summer to autumn)	-	mountains of western Asia	sun	twining	medium	15	4x-	5

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Family	Specie examples (common name)	Height x profile (max in cm)	Hardiness zone	Foliage	Flower colour (season)	Fruit	Origin	Aspect	Climbing mechanism	Vigor	Max weight (kg/m²)	Min height x optimum width of support (m)	Distance from wall (cm)
Passifo-raceae	*Passiflora caerulea* (passion flower)	1000x30	7	deep green	pale green, blue, violet (mid to late summer)	orange	southern Brazil	sun, shelter	tendrils	strong	15	5x3	8
Plumbagi-naceae	*Plumbago auriculata* (plumbago)	600x90	10	evergreen	light blue	-	South Africa	light shade to sun	lax rambler	strong	15	3x2.5	10
Polemo-niaceae	*Cobaea scandens* (cup and saucer vine)	2000x30	10	divided leaves	cup-shaped purple (summer)	-	Mexico	sun	tendrils	strong	15	2x2	8
Polygonaceae	*Fallopia balschuanica* (russian vine, mile-a-minute vine)	1800x60	4	fresh green	white (late summer to autumn)	-	central Asia	light shade to sun	twining	very strong	15	8x3	8
	Muehlenbeckia complexa (maidenhair)	300x60	8, 7	dark wiry	-	-	New Zealand	light shade to sun, shelter	twining	medium	10	2x2	5
Ranunculaceae	*Clematis armandii*	800x60	8	evergreen	white (early spring)	-	China	light shade to sun, shelter	leaf twiner	strong		4x3	-

	Clematis montana	1200x90	6	green or purple-bronze flushed	pink or white (early summer)	-	central and western China, Hyma-layas	light shade to sun	leaf tendrils	very strong	15	5x3	8

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Family	Specie examples (common name)	Height x profile (max in cm)	Hardiness zone	Foliage	Flower colour (season)	Fruit	Origin	Aspect	Climbing mechanism	Vigor	Max weight (kg/m²)	Min height x optimum width of support (m)	Distance from wall (cm)
Ranunculaceae (continued)	*Clematis orientalis* (lemon-peel clematis)	500x60	6	fresh green	golden-yellow bells (mid-summer to autumn)	fuffy seed heads	northern and central Asia	light shade to sun	leaf tendrils	strong	10	5x3	8
	Clematis rehderiana	600x90	6	dense growth	cream-coloured bells (mid to late summer)	-	China	sun, shelt	leaf tendrils	strong	15	4x3	8
	Clematis terniflora	1000x90	6	dark green	small, white, scented (autumn)	-	eastern Asia	sun, shelt	leaf tendrils	strong	15	6x3	5
	Clematis vitalba (old man's beard)	1500x90	4	multiple leaflet	small, white, scented (mid to late summer)	fuffy seed heads	Europe	light shade to sun	leaf tendrils	very strong	15	8x4	15
Rosa-ceae	*Rosa sp.* (rose)	900	-	-	various colors and size	red hips	-	light shade to sun	thorns	-	10		10

Schisan-draceae	*Schisandra chinensis*	900x90	8<9	oval	cream-colour (early summer)	red	far East	light shade best	twining	medium	20	6x3	15
Solana-ceae	*Solanum jasminoides* (potato vine)	600x60	8	evergreen	mauve-violet (summer)	-	South America	sun, shelter	scrambler	strong	15	3x3	5

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Family	Specie examples (common name)	Height x profile (max in cm)	Hardiness zone	Foliage	Flower colour (season)	Fruit	Origin	Aspect	Climbing mechanism	Vigor	Max weight (kg/m²)	Min height x optimum width of support (m)	Distance from wall (cm)
Tropaeo-loceae	*Tropaleoleum ciliatum*	1000x15	8	6-lobed	yellow (summer)	small, purple	Chile	top growth best in sun or light shade	twining	strong	10	5x3	5
Vitaceae	*Ampelopsis brevipedunculata*	600x60	9	yellow-orange in autumn	small green (summer)	purple, blue berrylike	north-eastern Asia	light shade to sun	tendrils	medium	15	3x2	10
	Ampelopsis megalophylla	1000x90	5		-	black	western China	light shade to sun	tendrils	strong	20	5x3	15
	Parthenocissus henryana	1000x30	7	white-veined, red in autumn	-	-	China	best in light or medium shade	suckers	strong	15	-	-
	Parthenocissus quinquefolia (Virginia creeper)	1500x30	3	palmate, red in autumn	-	-	eastern north America	light shade to sun	suckers	strong	15	-	-
	Parthenocissus tricuspidata (Boston ivy)	2000x15	4	gloosy, red in autumn	-	-	eastern Asia	light shade to sun	suckers	strong	10	-	-

	Vitis aestivalis (summer grape)	1500x90	3	dull green	-	black	central and eastern north America	sun or light shade	tendrils	strong	15	8x3	15
	Vitis coignetiae (crimson glory vine)	1500x90	5	rough-textured, crimson, scarlet (autumn)	-	black, grapelike	Japan	sun or light shade	tendrils	strong	15	8x3	15
	Vitis vinifera (grape vine)	900x60	6	lobed	-	luscious, edible	Cauca-sus	sun	tendrils	strong	15	5x3	15

Adapted from Dunnett & Kingsbury 2008 and Blanc 2008 (see full reference in references section).

Appendix 4. Examples of support needed for green facade's plants

Genus	species	Support: Vertical support	Round-cross section	Trellis with right-angle mesh	Trellis	Horizontal supports	Trellis with diagonal mesh	Preferably with angled cross-section, max cross-section of perimeter (mm)	Self - clinging
Actinidia	*arguta*	X	X	and widely spaces members					
	deliciosa	X	X	X					
	kolomikta	X	X	X					
Akebia	*quinata*	X	X	X					
Ampelopsis	*brevipedunculata*	X		X				70	
	megalophylla	X		X				70	
Araujia	*sericifera*	X	X	X					
Aristolochia	*macrophylla*	X	X	X					
Bignonia	*capreolata*	X	X	X					
Bougainvillea	*spectabilis*	X			X				
Campsis	*radicans*	X		X		X	X		
Celastrus	*scandens*	X	X	X					
Clematis	*armandii*	X		X			X	45	
	montana	X		X			X	45	
	orientalis	X		X			X	30	
	rehderiana	X		X			X	30	
	terniflora	X		X			X	45	
	vitalba	X		X			X	40	
Cobaea	*scandens*	X		X			X	45	
Cocculus	*carolinus*	X	X	X					
Decumaria	*barbara*								X
Eunymus	*fortunei*			recommended		recommended	recommended		X
Fallopia	*balschuanica*	X	X	X					
Fatshedera	*lizei*			X		X			
Ficus	*pumilla*								X
Hedera	*helix*								X
Hollboellia	*coriacea*	X	X	X					

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Genus	species	Vertical support	Round-cross section	Trellis with right-angle mesh	Trellis	Horizontal supports	Trellis with diagonal mesh	Preferably with angled cross-section, max cross-section of perimeter (mm)	Self - clinging
Humulus	*lupulus*	X	X	X					
Hydrangea	*petiolaris*			recommended		recommended	recommended		X
Ipomea	*hederacea*	X	X	X			X		
Jasminum	*officianale*			X		X	X		
Lonicera	*japonica*	X	X	X			X		
	periclymenum	X	X	X			X		
	tragophylla	X	X	X			X		
Menispermum	*canadense*	X	X	X			X		
Muehlenbeckia	*complexa*	X		X			X		
Parthenocissus	*henryana*								X
	quinquefolia						recommended		X
	tricuspidata								X
Passiflora	*caerulea*			X			X	50	
Periploca	*graeca*			X			X		
Plumbago	*auriculata*			X		X			
Pyrostegia	*venusta*	X	X	X					
Rosa				X		X	X	X	
Schisandra	*chinensis*	X	X						
Schizophragma	*hydrangeoides*				recom-mended	recommended			X
Sinofranchetia	*chinensis*	X	X	X					
Solanum	*jasminoides*	X	X	X			X		
Staunonia	*hexaphylla*	X	X	X					
Thunbergia	*grandiflora*	X	X	X					
Trachelospermum	*jasminoides*	X	X	X					
Tropaleoleum	*ciliatum*				X				
Vitis	*aestivalis*			X			X	70	
	coignetiae			X			X	70	
	vinifera			X			X	70	
Wisteria	*sinensis*	X	X	X					

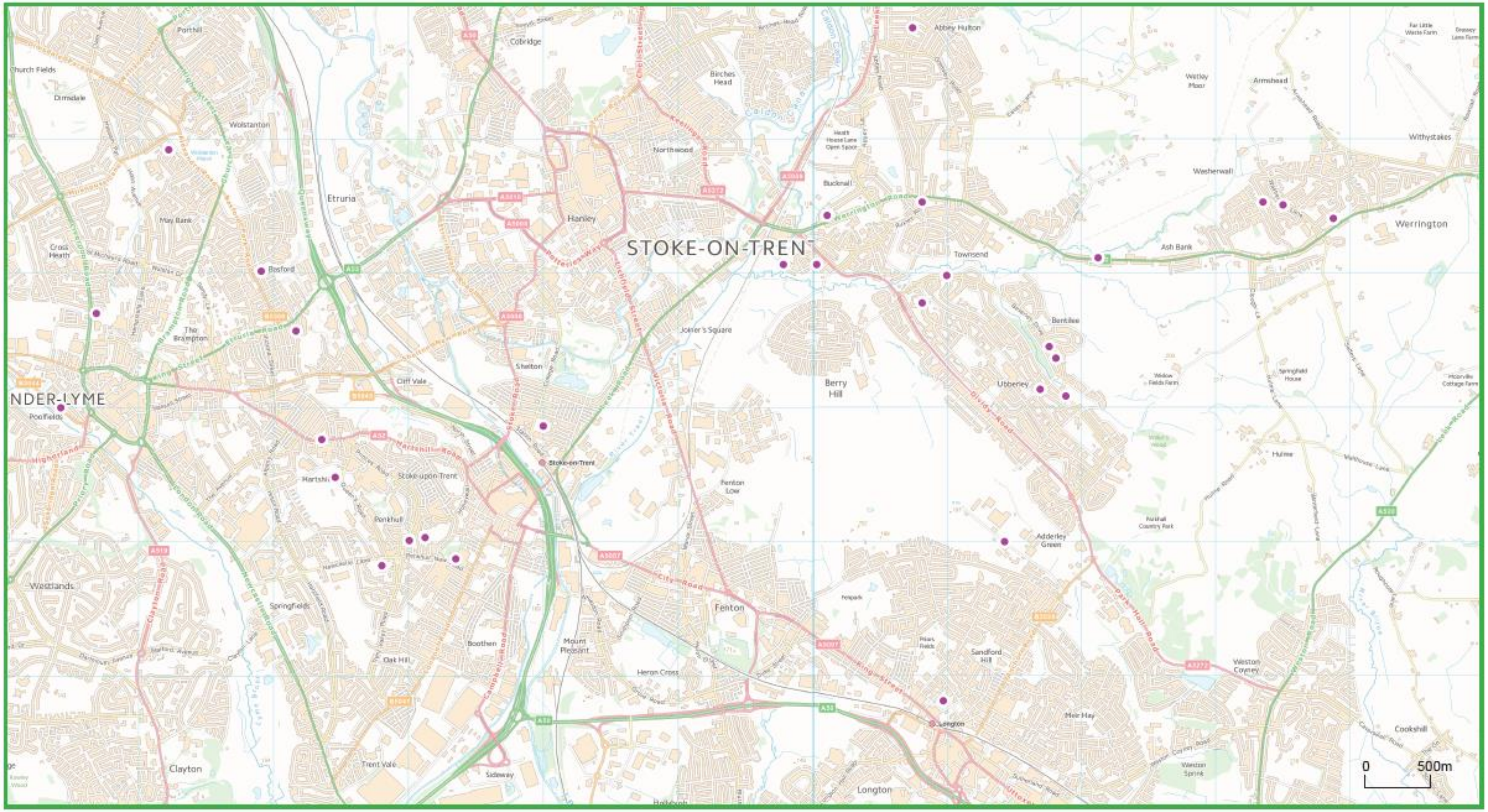
Adapted from Dunnett & Kingsbury 2008 and Blanc 2008 (see full reference in references section).

Appendix 5. Botanical composition of the studied Living Walls in London and Birmingham

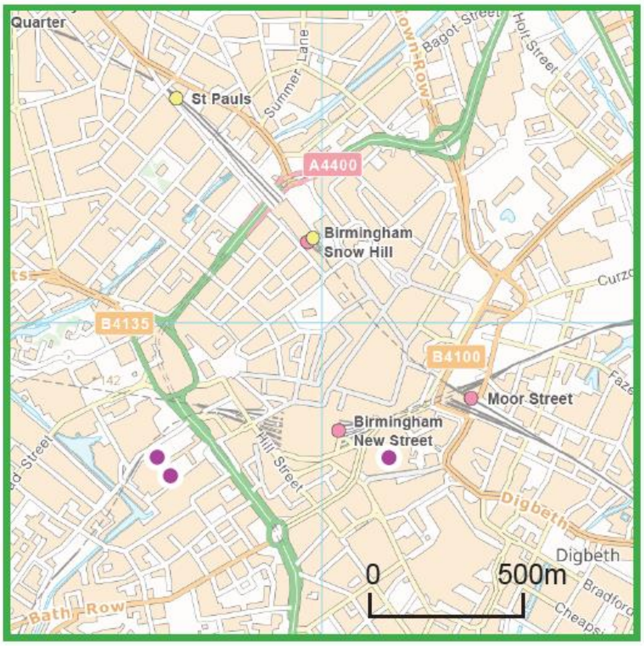
Scotscape	Mobilane	Treebox	Biotecture	Bin Fen (design by Treebox)	Grange Roofing ltd.
• *Amygloides sp.* • *Aspelium sp.* • *Bergenia sp.* • *Carex sp.* • *Euonymus sp.* • *Euphorbia sp.* • *Hedera sp.* • *Helleborous sp.* • *Heuchera sp.* • *Hosta sp.* • *Geranium sp.* • *Liriope sp.* • *Pachysandra sp.* • *Saraccocca sp.* • *Tiarella sp.* • *Vinca minor*	• *Ajuga reptans* 'Black Scallop' • *Arabis* 'Old Gold' • *Aubrieta* 'Double Pink' • *Bergenia* 'Ouverture' • *Campanula poscharskyana* 'Lisduggan' • *Chiastophyllum oppositifolium* 'Jim´s Pride' • *Cyrtomium fortunei* • *Dryopteris erythrosora* 'Prolifica' • *Heuchera* 'Jade´s Gloss' • *Heuchera* 'Marmalade' • *Heuchera* 'Midnight Rose' • *Lithodora diffusa* 'Heavenly Blue' • *Lonicera nitida* 'Maigrun' • *Phlox subutala* 'Emerald Cushion' • *Polypodium vulgare* • *Polystichum polyblepharum* • *Polystichum setiferum* 'Dahlem' • *Sedum spurium* 'Purpurteppich' • *Teucrium lucidrys*	• *Carex sp.* • *Eruca sativa* • *Heuchera sp.* • *Heuchera* 'Paris' • *Hedera sp.* • *Solanum lycopersicum* • Ferns	• *Acorus gramineus* 'Ogon' • *Carex testacea* • *Erysimum* 'Bowles Mauve' • *Euonymus* 'Emerald n' Gold' • *Euonymus* 'Emerald Gaiety' • *Euphorbia characias* 'Humpty Dumpty' • *Heuchera* 'Plum Pudding' • *Hypericum calycinum* • *Geranium macrorrhizum* 'Bevan's Variety' • *Lavandula augustifolia* 'Munsted' • *Lonicera nitida* 'Maigrun' • *Stachys byzantina* 'Silver Carpet' • *Veronica* 'Waterperry Blue' • *Vinca minor* 'La Grave' • *Waldsteinia ternata*	• *Carex sp.* • *Eruca sativa* • *Heuchera sp.* • *Heuchera* 'Paris' • *Hedera sp.* • *Solanum lycopersicum* • Ferns	• *Asplenium scolopendrium* • *Blechnum spicant* • *Heuchera* 'Palace Purple' • *Vica minor* • *Waldsteinia ternata*

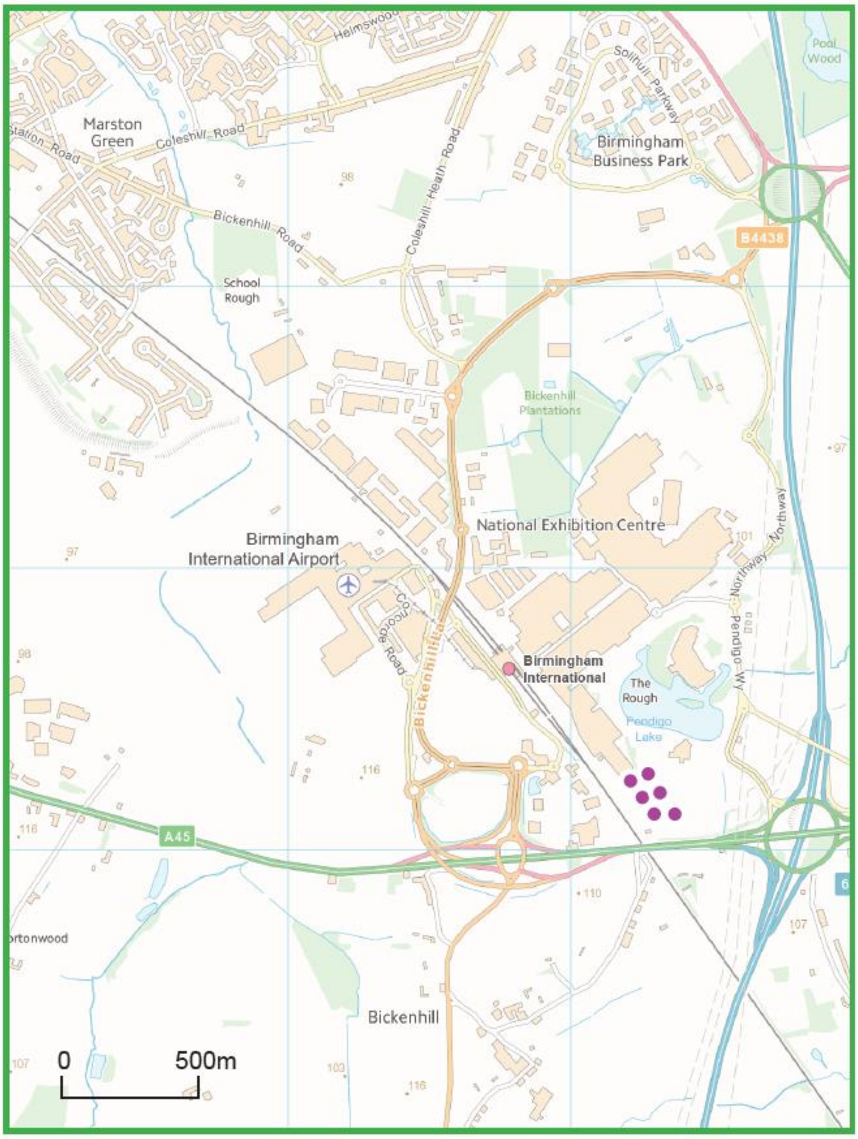
Lists given by the manufacturers.

Appendix 6. Map of studied green façades in Stoke-on-Trent and Newcastle-under-Lyme, Staffordshire, UK



Appendix 7. Map of studied living walls in Birmingham





Appendix 8. Map of studied living walls sites the Greater London Area