Urban naturalistic meadows to promote cultural and regulating ecosystem services

By:

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

The University of Sheffield

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January 2018

Abstract

This thesis examined the ecosystem services delivered by a new type of vegetation comprised of grasses and forbs organised in biodiverse naturalistic meadows. The study site was a 500 metres retrofitted linear greenway, the Grey to Green, installed in Sheffield (UK) city centre. A street survey showed users highly appreciated the vegetation and had an improved the perception of the urban environment and thus established the delivery of cultural ecosystem services. By means of a questionnaire and micro-climatic measurements, a thermal sensation scale for Sheffield was defined. In addition to evidence for the role of physiological acclimatisation, a link was found between appreciation of the green space and tolerance to thermal discomfort. The influence of psychological factors on thermal comfort was further investigated using a visual questionnaire. Results highlighted interactions between thermal preference, thermal expectation, landscape appreciation and long-term experience. The microclimatic regulating services of meadows was demonstrated via a yearlong comparative study of surface temperature against that of shaded and exposed turf and concrete. The results highlighted meadows have a measurable impact on reducing the Urban Heat Island effect; and, at times, more efficiently so than trees. The environmental simulation software Envi-Met was tested against field data and was showed to predict realistically surface temperature. This thesis demonstrated the usefulness of urban meadows in cultural and regulating ecosystem services delivery. They may ease surface heat accumulation, improve perceptual qualities of the urban environment and improve the sensation of thermal comfort. Thus, they contribute to making cities more liveable.

Acknowledgements

Science is more than a body of knowledge, it is a way of thinking,
a way of sceptically interrogating the universe.
Carl Sagan

I am much obliged to the University of Sheffield for funding this Ph.D. thesis and giving me the privilege to undertake this body of work.

I would like to extend my gratitude to my supervisors, Nigel Dunnett and Virginia Stovin, for supporting me through this arduous process. From transforming the original brief into a viable research project to guiding my thought process and ensuring I stayed on track, I am deeply grateful for the mentoring they provided to the junior researcher that I was.

Interdisciplinarity research is as much about creating new knowledge as it is to share it. This thesis is my own responsibility but a certain number of people have participated to this undertaking.

Abigail Hathway has provided me with most helpful guidelines and tips on engineering and climate science related topics, her mentoring ensured I applied best practices from the start. Her generosity for lending me all her equipment enabled me to undertake the outdoor experiments.

Jean Russell has been of invaluable help in guiding me through the subtleties of statistical analysis. I must credit her patience and efficiency in filling the gaps of my statistical knowledge.

I would like to thank Ross Cameron and Nicola Dempsey for their feedback and guidance at various stages of my thesis.

I would like to thank Zac Tudor, Sam Thorn and Lucia Lorente-Arnau from the Sheffield City Council, not only for their time introducing me to the Grey to Green but for their kindness in helping me access the site.

I would like to warmly thank Simon de-Ville for sharing the Hadfield roof data and Julian Briggs for granting me access to the Solar Research Group database; without their help the project would not have progressed.

Mingyu Jiang helped me tremendously by providing me with the necessary visualisations for the online questionnaire.

On a personal basis, I would like to extend my warmest thanks to my wife Seenu for bearing with me on a daily basis, helping me overcome the many hurdles along this path. I would like to thank my parents, grand-parents and siblings for their belief in me. In particular, my most sincere appreciation goes to Geneviève Lhomme for her infallible support and constant motivation. If I now stand proudly on my achievements, it is because my close friends and family have instilled in me a sense of duty and never failed to pick me up when I stumbled.

My last thought goes to Denise Duchadeuil who passed away during this process, I will keep lovingly your memory.

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Chapter 1: Context and research aims

1.1 Introduction

The present thesis evaluates the usefulness of using a type of vegetation known as meadow or grassland in an urban context. These ecosystems are dominated by grasses and flowering plants with little to no trees and other woody species. They could constitute an interesting alternative to more traditional urban landscape forms but little is known on the positive or negative effects they may have on the quality of life of urban dwellers and liveability of cities. This thesis tackles this lack of knowledge through the framework of ecosystem services which are quantifiable or observable outputs produced by a biological community within its physical environment. This work assesses such outputs in the light of the benefits humans could derive from the existence of a biological community, here meadows in urban environments. Three aspects of ecosystem services are the focus of this research: the effects an urban meadow could have on microclimate, on thermal comfort and on psychological well-being. Each of these concepts and the research approaches will be further introduced in the present chapter.

The present body of work received Ethics Approval (Reference Number: 009939) for the street questionnaire presented in Chapters 3 and 4, the online visual questionnaire presented in Chapter 5. Consent was sought from participants and they were explained the gist of each questionnaire. Data was handled in accordance with University Policy and is authorised to be published in the present. The outdoor experiments presented in Chapter 6 received Health and Safety approval which was bundled within the Ethics Review. This thesis is supported by the University of Sheffield Interdisciplinary Scholarship: Future Cities.

Given the pluridisciplinarity of the work engaged and the diversity of methods employed to complete this thesis, please note that this thesis departs from a traditional format. In line with the University of Sheffield guidelines (Code of Practice for Research Degree Programmes. 2017 – 2018), this thesis contains an introduction and a conclusion that are relevant to the whole body of work by setting and discussing the general aim of the research undertaken. The "Results" chapters have been written akin to publications. This means that each provide their own introduction, methods and discussion sections.

When appropriate, links were made between findings of different chapters but not fully re-demonstrated to avoid redundancy and unnecessary length.

1.2 Issues of liveability

This body of work emerged from the founding brief and guiding principles put forth by the “Future Cities: design, engineering and urban retrofit” network. Its motivation was to apply interdisciplinary approaches to tackle current urban issues such as the development of innovative solutions to improve sustainability and liveability.

Sustainability and liveability are complementary concepts which respective definitions and areas of overlap have been largely debated in the literature (Gough, 2015). Some authors have even preferred using different concepts altogether such as “Quality of Life” versus “Environmental Quality” (van Kamp *et al.*, 2003). In this body of work, the concept of liveability took preeminence since it was posited that the well-being of natural environments or ecosystems precluded human well-being (Lele *et al.*, 2013). Additionally, the focus on urban environments, which are by definition man-made spaces designed for human life, prompted the choice of the more anthropocentric lens that liveability constitutes.

Liveability is a rather all-englobing concept that includes the basic biological needs of a human (such as shelter and food) as well as higher order needs which would fall into psychological, social (inter-personal) and spiritual dimensions (Ruth and Franklin, 2014). An environment is deemed liveable when it favours well-being in these dimensions to the people living in it (Kashef, 2016). Liveability thus refer to the environment’s characteristics that allow for these needs to be met, whether from a direct transaction with the environment or the environment being a platform or a context to the delivery, the degree to which these needs are met and the well-being which ensues (Antognelli and Vizzari, 2016; van Kamp *et al.*, 2003).

In modern times, liveability in cities is compromised. The expansion of cities and rampant urbanisation has caused a plethora of environmental issues. For instance, the expanses of hard surfaces forces stormwater to be concentrated in increasingly ill-adapted sewers thereby increasing the likelihood of floods and combined sewers overflow putting private properties, road, energy and information networks and public infrastructure at risk (Stovin and Swan, 2007). The built environment along with the concentration of energy-demanding activities has adverse effects on the local climate by creating a lasting local peak of high temperatures known as the Urban Heat Island effect (Smith and Levermore, 2008). Not only does this elevation of temperature favour the creation of pollutants such as ozone, it produces a higher thermal stress which poses a threat to the range of outdoor activities which can be practised, it reduces night time recovery and finally it generates a large range of risk factors to human health (Kleerekoper, van Esch and Salcedo, 2012). Aside from the environmental impediments, which are likely to worsen with climate change, increased population density and extent of cities (Smith and Levermore, 2008; Gaffin, Rosenzweig and Kong, 2012), there are equally vital social and cultural needs which are not properly met if at all. However, as these are usually underpinned by the provision and access to socio-economic benefits, services and opportunities, these lie outside of the scope of this project. Indeed, this body of work is concerned with how urban spaces may provide a foundation upon which liveability may be achieved and one such way is to create, or retrofit, green infrastructure in the existing urban fabric.

1.3 Green Infrastructure to deliver ecosystem services

Green Infrastructure (GI), understood in an urban context, are "hybrid infrastructures of green spaces and built systems […] that together can contribute to ecosystem resilience and human benefits through ecosystem services" (Demuzere *et al.,* 2014). The key component of GI is to provide a physical structure for ecosystems to live on (Tzoulas *et al*, 2007). In turn, these ecosystems, by their very existence, structures or processes within and between their biotic and abiotic components have certain functions also known as ecosystem services (De Groot, Wilson and Boumans, 2002; Escobedo, Kroeger and Wagner, 2011). To date, the most extensive framework regarding ecosystem services is the Millennium Ecosystem Assessment (2005). It states that these functions may be classified into four categories (see Figure 1.1). In the first place, there are supporting functions which permit ecosystems to be and flourish; these include water and nutrient cycling, soil formation and retention, tissue and biomass formation etc. These primary processes support other functions such as regulation services, which may range from flood prevention, purification of the air to climatic stabilisation, and provisioning services. The latter, through the supply of food and drinkable water for example directly contributes to human liveability by fulfilling its basic needs. Green Infrastructure through the provision of the fourth ecosystem service, the cultural function, participates in providing a place for interaction with ecosystems themselves or a platform for higher order needs, such as social or religious gatherings, to be met. Ecosystem services seen through the lens of anthropocentric liveability may then be defined as "*the benefits (or the drawbacks) humans derive, directly or indirectly, from the existence, functioning and exploitation of ecosystems"* (definition derived from de Groot, Wilson and Boumans, 2002; Escobedo, Kroeger. and Wagner, 2011; Fisher, Turner. and Morling, 2009). In short, ecosystems can enhance liveability by providing services and their delivery is mediated by green infrastructure in urban contexts.

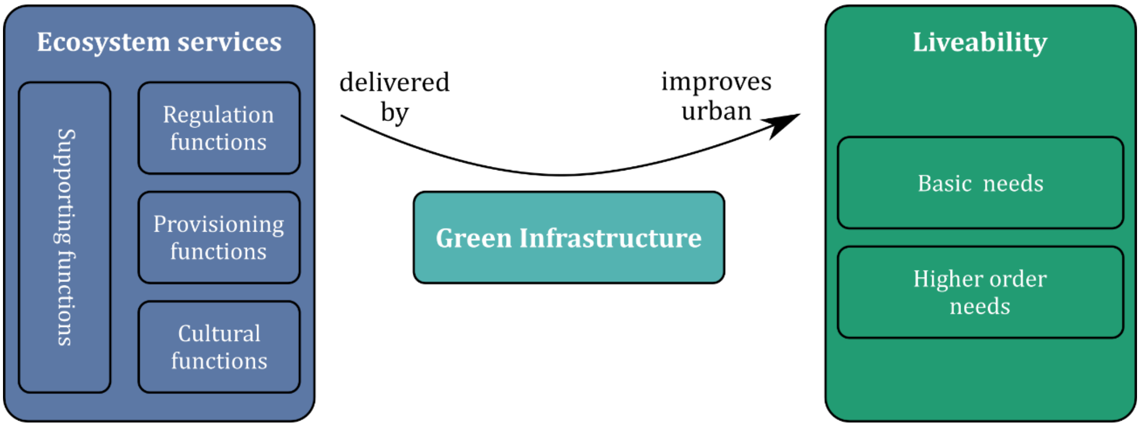


Figure 1.1: Schematic highlighting the link from the existence of ecosystems to their mode of delivery via Green Infrastructure to achieve liveability in cities.

In effect, GI has been linked to the improvements of many current urban issues. Numerous studies have highlighted the usefulness of large extents of greenery, city parks or urban forests, in countering the abnormal temperature elevation (known as the Urban Heat Island) by significantly cooling the air (Yu and Hien, 2006). This phenomenon named Park Cool Island has been shown to occur worldwide (Erell, Pearlmutter and Williamson, 2011). This cooling effect (a regulating ecosystem services) is known to extend beyond the physical space of the planted area (Jansson, Jansson and Gustafsson, 2007) and can affect large parts of the city. To continue on this example, a park also enhances liveability within its boundary by providing a wide range of cultural ecosystem services. Users may come to parks to fulfil higher order needs such as "relaxing and "be in [contact with] Nature" (Chiesura, 2004) or searching for a "recreational space" (Home, Bauer and Hunziker, 2010). Urban GI acts indeed as a platform to increase well-being even when such infrastructure is understood as a network of small planted areas. Sarkar *et al.* (2015) demonstrated that people walked more in streets which included more street trees in London. This translated into increases in two key variables: propensity to walk and distance walked, as the number of single street trees increased. As walking is perhaps the most common form of physical activity, it participates in maintaining good health. In this example, GI is thus linked to healthy behaviour possibly mediated by an improved perception of the street environment due to the presence of trees. Indeed, mere contact with vegetation, even in urban environments, has been shown to improve cognitive processes and mood (Hartig *et al.*, 2003).

Ecosystems, and green infrastructure for this matter, are also known to render conflicting services. These conflicts may arise from different degrees of proximity to the actual space. Fisher, Turner and Morling (2009) give the example of a rainforest which acts as a global carbon sink thereby reducing the impact of anthropogenic pollution as a regulating service but, locally, as a supply of fuel which falls under provisioning services to highlight how certain functions produce contrasting services. In a similar vein, Church (2015) reports a disjunct between resident appreciations of swales even though these provide water quantity management. Their non-traditional look departed from the beauty standard and residents reported dissatisfaction from these vegetated areas. Here, the conflicts arose due to the constraints imposed on green spaces for use as stormwater management and their importance as a local amenity. Hence, as eluded to in the definition of ecosystem services, there may also be drawbacks to functioning ecosystems.

When considering ecosystems services in an urban environment, it becomes apparent that the material production or the physical impact of green infrastructure must be examined alongside its cultural or social contribution. Within the highly fabricated places that cities are, green infrastructure must not only fulfil basic needs but also users' higher order endeavours. To deal with this ambivalence, this project chose a socio-technical approach. The term socio-technical approach is borrowed from the organisational and systems engineering fields. In its original context, the basis of this approach was to ensure that a system meets technical performance and end user satisfaction (Bostrom and Heinen, 1977). It grew out of the need to embed technical or organisational systems in social contexts (Mumford, 2000). This body of work translated technical systems into eco-systems. Effectively, this approach considers the simultaneous delivery of different ecosystems services. To achieve liveability in its strictest acceptation, which is the intersection of community harmony and environmental viability (Shafer, Lee and Turner, 2000), regulation and cultural functions of ecosystems must be examined simultaneously.

1.4 Limitations in current Green Infrastructure research

Studies analysing the regulating services of green infrastructure typically focus on trees (Kleerekoper, van Esch and Salcedo, 2012; Edmondson *et al.*, 2016; Salmond *et al.*, 2016 for example). This fact is explainable as numerous studies have asserted the usefulness of trees to mitigate the Urban Heat Island effect and to provide respite from the sun to dwellers. Shashua-Bar and Hoffman's study (2000) has become a reference regarding the microscale benefits of GI by notably reporting a 3°C reduction in air temperature around the immediate vicinity of a tree. Deciduous species can also be used advantageously in Northern countries to allow radiation onto the street in winter when they have shed their leaves (Nikolopoulou, 2004). However, trees cause numerous disservices, notably because of their supporting services which includes their growth habit. For instance, an ill-placed tree may divert air flows and cause cyclic flows causing accumulation of pollutants at a person's levels (Erell, Pearlmutter and Williamson, 2011). Escobedo, Kroeger and Wagner (2011) established a long list of drawbacks caused by street trees and urban forests, which includes damage to buildings and sidewalks, monotonous planting as well as financial and carbon cost of maintenance. They also evoked that they may instil fear. This potential interaction between treed vegetation, its arrangement, and a sense of insecurity has been highlighted by Jorgensen, Hitchmough and Calvert (2002) and is presumed to be caused by their shape that restricts "openness". This lack of visual permeability may then cause a natural "biophobic" reaction (Ulrich, 1993). Additionally, the delivery of cultural services, particularly appreciation of the aesthetic components, is tied to the views and particular disposition of a local community (Bourassa, 1990; van Kamp *et al.*, 2003). This was, for instance, showed in Knez and Thorsson (2008) where cultural differences between Swedish and Japanese as well personal attitude towards outdoor activities had a significant effect on the reported pleasantness and aesthetic appreciation of the parks they were into. As such, limiting green infrastructure to a restricted set of options is unlikely to fulfil the needs of every local community, which highlights the desirability of other plant forms.

From an ecosystem services perspective, large scale vegetated areas such as parks or urban forests have been extensively studied (such as in Chiesura, 2004). Only a limited amount of studies address an intermediate scale, between the single tree and the urban park (see Felson and Pickett, 2005 for example). This might, however, become the most relevant scale to local authorities worldwide. As urbanisation has progressed, space for big urban parks might not be available anymore but opportunities to retrofit smaller scale GI may be plentiful (Felson and Pickett, 2005; Stovin, Swan and Moore, 2007). There is therefore a research gap to be filled on intermediate scale vegetated areas (Demuzere *et al.*, 2014). Emerging research is indeed suggesting that effects at this scale are not negligible, particularly on cognitive restoration in the case of pocket parks (Peschardt, Stigsdotter and Schipperrijn, 2016) but much remains unknown, particularly on their regulating services.

1.5 Meadow vegetation as a potential multi-functional ecosystem

A promising alternative to trees is meadow-dominated vegetation. Southon *et al.* (2017) after reporting that residents were not only receptive but also preferred species-rich meadows at the expense of traditional cues of human intervention (such as neatness and winter cutting) advocated for this vegetation to be studied further as a credible urban form. Given the growth habit of grasses and forbs, there is ample room for biological and geometric diversity. Contrary to a traditional horticultural approach to landscaping which necessitates larger man power and financial means, meadows may provide a more ecologically oriented approach by necessitating less labour. Their diversity of shape and colours are aesthetically important, they do not require to be mown extensively (Hitchmough and Woudstra, 1999). The access to taxonomic diversity also entails the possibility of matching the vegetation to a site's specificities as well as favouring invertebrate and avian populations (Hitchmough and Fleur, 2006).

Numerous factors still impede their use as a credible alternative to trees or as their adoption as part of traditional green spaces. Indeed, the regulating services meadows, or herbaceous vegetation in general, could provide is mostly limited to turf grass (Armson, Stringer and Ennos, 2012 and Janik *et al.*, 2015 for instance). This underlines the limited knowledge of the diversity of three-dimensional arrangement GI can offer. Indeed, beyond the two extremes that are short, regularly mown turf (used only as a reference in

Klemm *et al.*, 2015 for example) and mature trees with large canopies, little knowledge has been produced to date.

An *à propos* retrofitted green space project arose in Sheffield's City Centre that featured a meadow-dominated vegetation, the Grey to Green. Designed as a linear greenway, it saw the transformation of a grey avenue into a greened street with a reduced size road and the inclusion of planted beds on either side of one of the sidewalks. This scheme was an opportunity to undertake research on urban meadow vegetation and the regulating and cultural ecosystem services it may provide

1.6 Aims, research approaches and objectives

So far, it has been established that liveability regroups a variety of factors that together contribute to human quality of life, both from physical and psychological perspectives. Plants, and by extension green spaces, may counterbalance risk factors that occur within the built environment via the delivery of ecosystem services. In this context, it was noted that small-scale green spaces and meadow vegetation are landscape choices that received comparatively less attention. Hence, the overarching aim of the present thesis is to examine some of the cultural and regulating ecosystem services delivered by urban meadows (shown in Figure 1.3).

As a first step, the Grey to Green which served as the study site in this body of work was characterised. As a multi-purpose green scheme, the Grey to Green was built with water detention in mind and took the approach of providing a grass and forbs dominated vegetation planted in a naturalistic planting style (CEEQUAL, 2016). This characterisation, which is reported in Chapter 2, has two objectives. The first one is to establish a description of its main features: SuDS, planting and economic context. The second objective of this chapter is to provide a list of the ecosystem services the scheme is expected to provide by design.

Within cultural ecosystem services, two aspects of the transaction with a green space were selected. It was unknown what the public's reaction to a meadow-dominated vegetation arranged in a naturalistic manner would be within a city centre context would be. Indeed, contradictory theoretical views existed on this topic. Nassauer (1995) claimed that in urban environment a lack of visible human care and "messiness" entrained rejection. In contrast, in traditional environmental psychology, savannah-like environments have been found to elicit a "biophilic" reaction (Ulrich, 1993). Given the lack of knowledge in this regard, it seemed evident that users' acceptance of the planting and the scheme would constitute the first objective of this thesis. The transaction with an instance of "nature" is known to provoke emotional and intellectual reactions. The second objective was therefore to evaluate how the planting might have improved or worsened various perceptual dimensions of the streetscape the scheme was in. Both of these objectives are treated in Chapter 3.

The latter objectives were also considered as a first step towards understanding the Grey to Green's potential effect on thermal comfort; which constituted the second research approach. Defined as the satisfaction with the thermal environment (Taleghani *et al.*, 2015), outdoor thermal comfort has been identified as one of the key contribution of vegetation to the liveability of cities (Demuzere *et al.*, 2014). Once again, data was limited on the potential improvement of thermal comfort by meadow vegetation. As highlighted by earlier studies, thermal comfort was not solely dependent on climatic parameters but also on perceptual and psychological phenomena (Nikolopoulou, Baker and Steemers, 2001). Knez *et al.* (2009) proposed a conceptual model of thermal comfort (summarised in Figure 1.2) where the "place" a person is in affects them in a variety of ways through its microclimate and its spatial configuration. However, depending on certain factors which include a person's prior experiences, their attitude and beliefs as well as their activity level and reason to be outdoors, the effect of a "place" is moderated to produce a range of responses.

Thus, probing users' thermal sensation and establishing a local thermal comfort scale, based on both their reported sensation and microclimatic parameters, constitutes the first objective in this research approach and is reported in Chapter 4. It follows that the influence of psychological factors may be inferred where the reported sensations do not match the expected or calculated comfort. Thus the second objective was to evaluate, notably using results from Chapter 3, the effect of certain psychological and physiological factors on the reported thermal comfort levels.

To add to the growing body of literature on the psychological components of thermal comfort, a final component was added to the thermal comfort approach. New work suggested that a person's experience shaped their thermal sensation by leading to the creation of engrained thermal preference and thermal expectations in relation to the "Place" they were in (Lenzholzer, Klemm and Vasilikou, 2016) To continue further this discussion of the impact of psychological factors on thermal comfort, Chapter 5's objective is to establish the existence and relationship between certain psychological factors of thermal comfort such as thermal preference, thermal expectation and landscape preference.

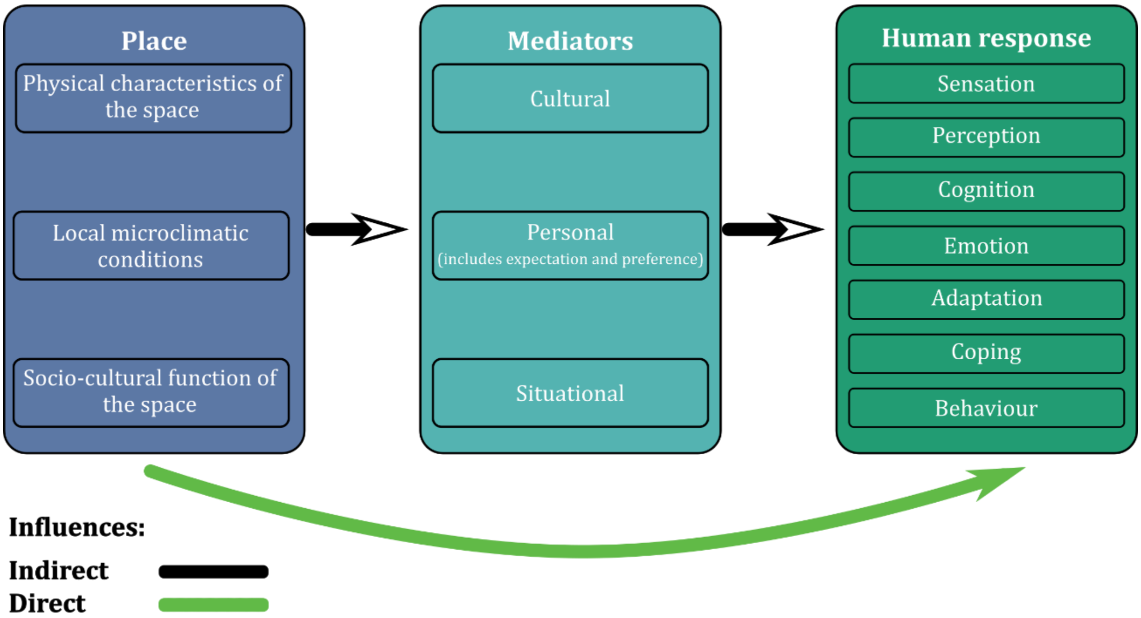


Figure 1.2: Simplified conceptual model of thermal comfort, proposed by Knez et *al.* (2009), which incorporates psychological processes in the emergence of thermal sensation.

Within regulating ecosystem services, which represents the third research approach, it was found that there was a gap of knowledge in the microclimatic effect of meadow vegetation. In urban contexts, it is particularly relevant to evaluate how green spaces reduce the urban heat island effect; the latter being a localised and persistent accumulation of heat within the urban space. One way to evaluate if a particular type of land cover participates to the heat island or reduces it is to measure its surface temperature throughout the day and compare it to surfaces such as concrete which favours heat accumulation and increase in temperature. In this regard, meadow vegetation with its complex three-dimensional structure of herbaceous plants characterised by dense ground cover, heterogeneous heights and growth habits has received limited attention. The objective of Chapter 6 was thus to monitor the meadow vegetation of the study site to understand how its surface temperature changed over the course of a 24 hours cycle, throughout the year, when compared to other surface types such as tree vegetation, turf grass and concrete.

On the one hand, empirical studies may be constrained by such things as access to a site, equipment or time. On the other hand, simulation programs may help researchers to evaluate the effect of a land use without needing extensive site surveying or help designers in considering different landscaping scenarios and their effect on the microclimate. For this reason, it was chosen to evaluate a modelling tool named Envi-Met. The literature indicated that some work had been carried out to validate this 3D climatic simulation software in a variety of contexts such as the effects of street trees and urban forms on the air and ground temperatures (Taleghani *et al.*, 2015) but not with respect to herbaceous vegetation. Hence, in an attempt to cover this gap, the objective of Chapter 7 is to test the validity of this program by modelling simple meadows and comparing the simulated surface temperature with the one empirically measured and some obtained from literature.

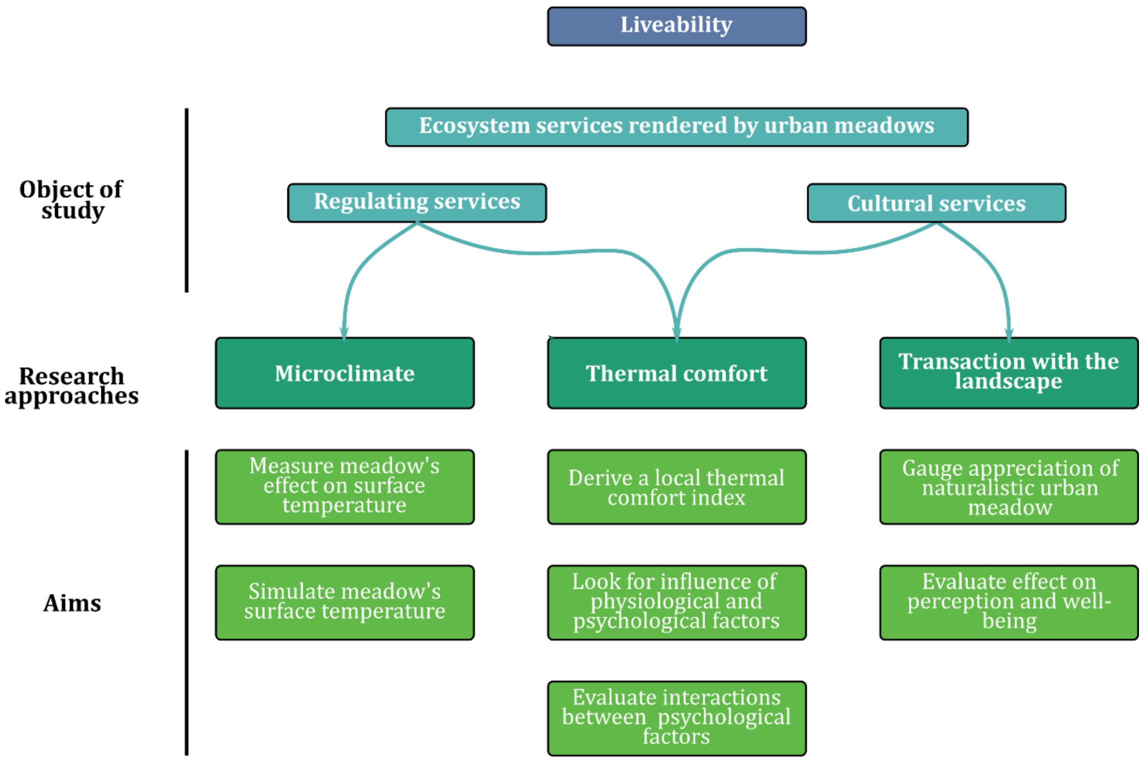


Figure 1.3: Summary of the object of study down to individual research objectives.

Chapter 2: The Grey to Green: site characterisation

2.1 Introduction

The Grey to Green is a complex greenway was retrofitted in Sheffield city centre (UK) and is the study site for a major part of the present. Being planned as a multi-purpose scheme, it has a number of features such as SuDS elements, specific planting (both in terms of species choice and arrangement) and art installation. At its core, it is intended to fulfil a number of ecosystem services both regulating and cultural. This chapter is intended as a general presentation of the Grey to Green scheme and the main objective is to detail each of the main components of this novel greenway: its general location, its water management service and its planting. This scheme was also placed within the established research framework, which is the optimisation of ecosystem services delivered by Green Infrastructure. To this effect, the various ecosystem services that the scheme is expected to provide are listed at the end of the chapter.

2.2 Primary data collection

The first phase of the Grey to Green scheme was implemented in February - March 2016 in the city centre of Sheffield (United Kingdom). At the time of writing, there was not any scientific literature available on the scheme but background material was available (CEEQUAL, 2016). Additionally, most documents relating to the design, plans and rationale of the scheme were not accessible via the Internet. Hence, the amount of readily accessible information was limited but could be made public on demand. A mix of data gathering methodologies were used. Initially, a press review was made using a standard research engine as well as the Nexis® database. (LexisNexis, 2016). In both cases, the words “grey to green” AND “Sheffield” (“AND” was used to mean both words must be present) were input. The articles were then reviewed individually and selected if they had a relationship with the topic at hand. All duplicates, articles that were too vague or repeating similar information were discarded from the press review.

In addition to the press review, a search for official documents was undertaken. These can take the form of press releases from Sheffield City Council (such as Sheffield News Room, 2015a, for example) or official reports issued on the City Council’s website.

To complete this search, additional documents were obtained by asking directly to landscape architects from the City Council.

2.3 Characterisation of the Phase 1 of the Grey to Green scheme

2.3.1 Overall plan

Phase 1 of the Grey to Green scheme is situated in the northern part of Sheffield's city centre (coordinates: 53°23 N, 1°28 W, elevation: 52 metres). It is situated in a central part of the city, neighbouring the South Yorkshire Police Station, the Law Courts and the Family Courts as well as numerous hotels, businesses and administrative spaces. Just north of the centremost part of the city, it is also right next to the River Don and next to the confluence with Sheffield's other river, the Sheaf. The Grey to Green scheme is mainly installed along two streets: West Bar and Bridge Street, technically covering a length of 493 metres (see Figures 2.1 and 2.2).

West Bar is the street that underwent the most changes. From an original four lanes, the road was reduced to two, which freed considerable amounts of space (Sheffield News Room, 2015a). Along its north side a number of planted areas with meadow-dominated vegetation have been installed. The opportunity to add some trees was also seized. The south side of the street was also modified by replacing the tarmac with permeable pavements.

Moving eastward, the bottom of Snig Hill received some modifications as well with some planted areas on the east side and permeable pavement on the west side. The smaller area to the north, called Love Square (shown on Figure 2.2), is a work in progress. As funding is obtained and made available, the City Council plans to progressively turn this brownfield site into a recreational rain garden (European Union News, 2014). The remainder of Bridge Street has been refurbished with permeable pavement.

A last comment on the overall design concerns the road redesign (see Figure 2.1). Indeed, its size has not only been reduced but no separating markings between the two new lanes were put. In effect, removing markings should have a psychological effect on the drivers, requiring more attention, leading to more cautious driving behaviour and hence to traffic calming (Tudor, 2016). Lastly, the speed limit has been reduced to 20 mph on the West Bar portion of the road (Sheffield City Council, 2015d).

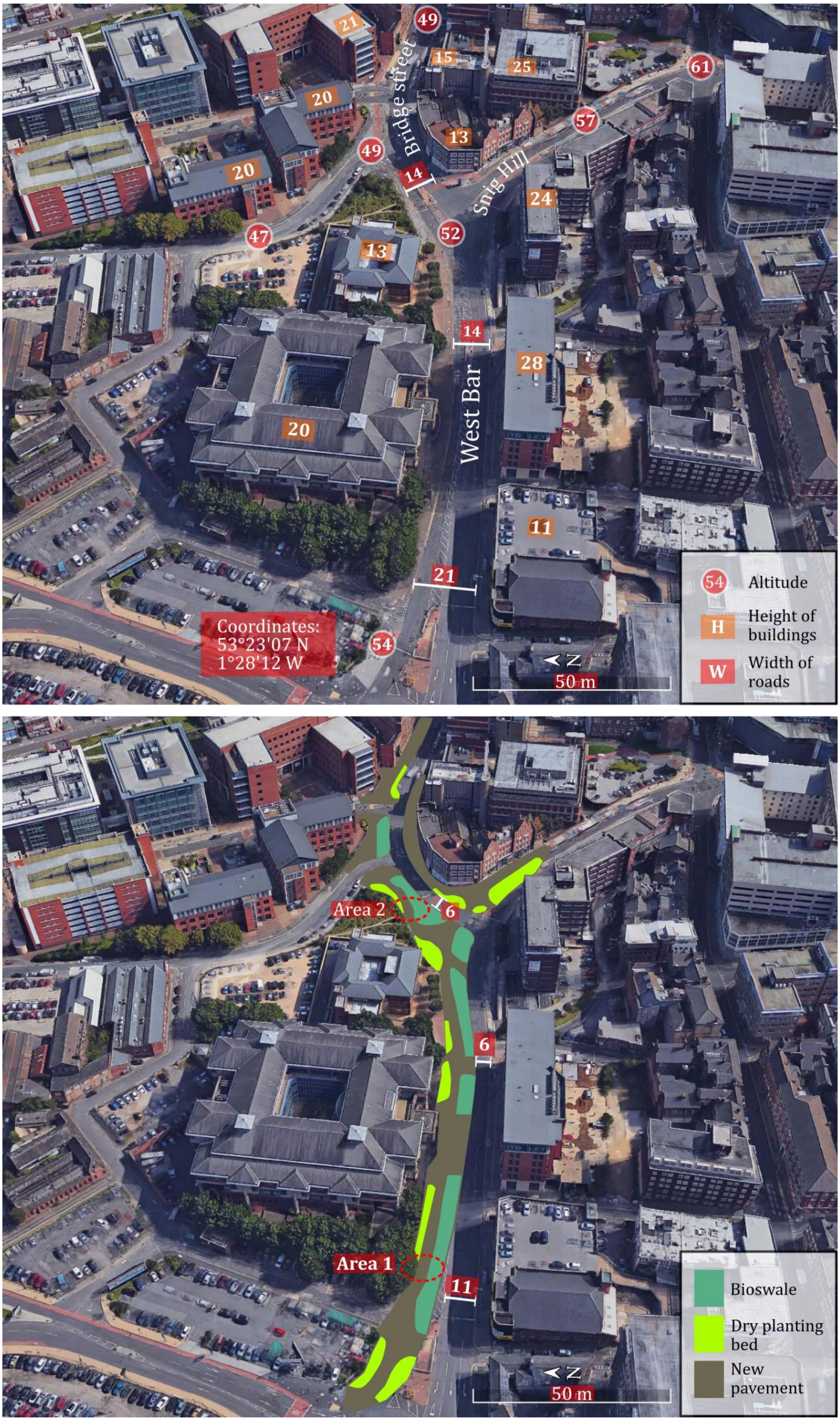


Figure 2.1: 3D view of the study site before and after retrofit of the Grey to Green Phase 1 scheme. Area 1 and 2 are where measurements for Chapter 6 were made (modified from Google Earth Pro images).

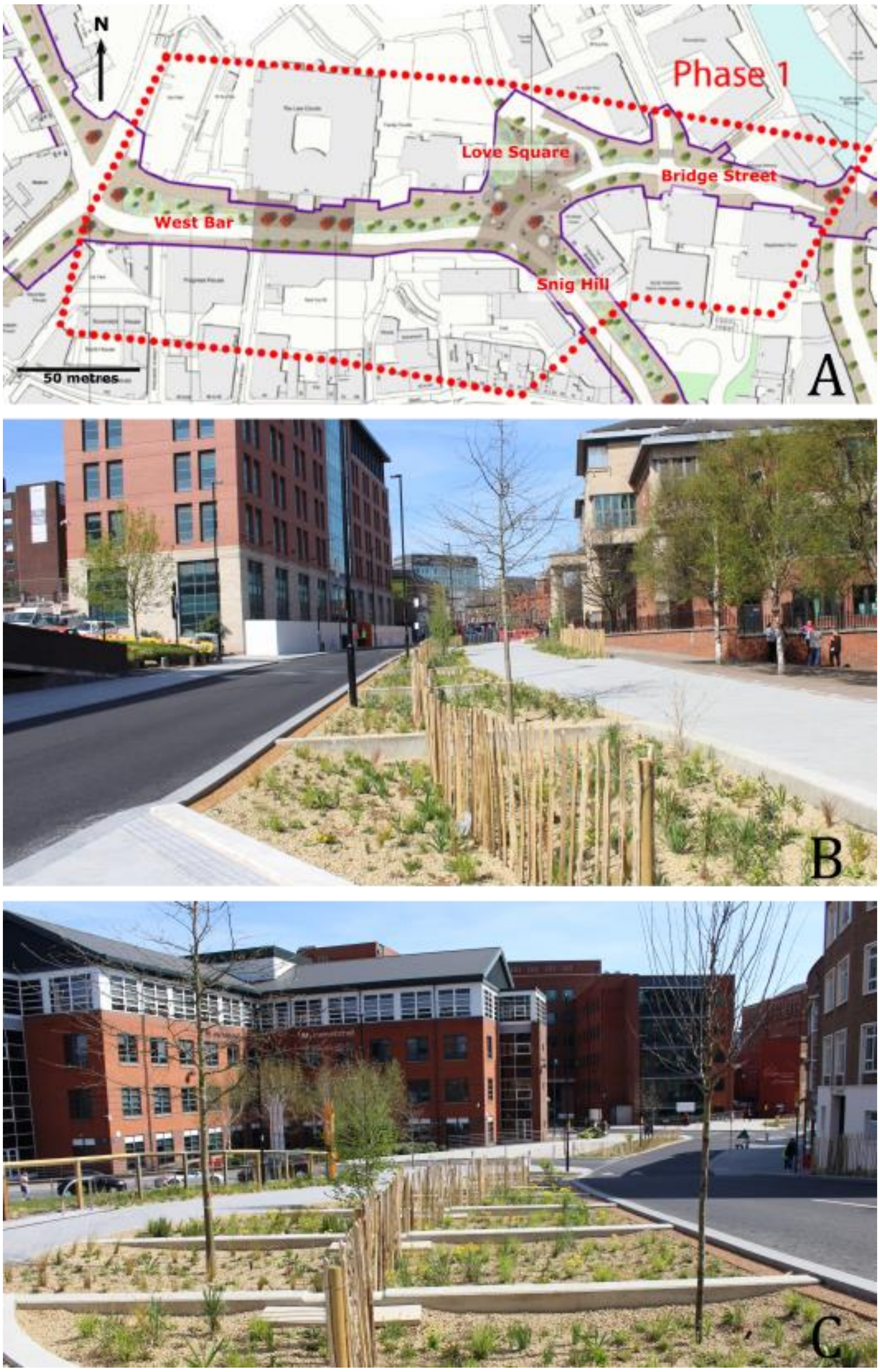


Figure 2.2: Various views of Phase 1 of the Grey to Green.
A. Plan of the scheme (reproduced and modified from Sheffield City Council material).
B. View from Love Square looking down West Bar.
C. View from Love Square looking down Bridge Street (author's photographs, both taken in May 2016).

2.3.2 The SuDS elements

Because part of the rationale for the Grey to Green scheme was for it to function as a Sustainable Drainage System (SuDS), the concept of SuDS must first be introduced. SuDS are designed systems which incorporate both ecosystems and man-made infrastructures (see Figure 2.3). The core function of a SuDS is to reduce and treat storm water runoff (Wilson, Bray and Cooper, 2004; Susdrain, 2012, Woods Ballard *et al.*, 2015) in a way that is closer to or mimics natural systems. It is thus a combination of quantitative easement and qualitative water treatment within a single scheme. At the same time, it serves as an amenity, whether urban or not. This is an important factor, as SuDS are designed to be incorporated within urban and rural landscapes as functional infrastructures (Digman *et al.*, 2012). As such they are tied to the context in which they are used as well as having an impact on their environment. As an example, a rain garden can also be utilised as a recreational space or even as a botanical garden for educational purposes. Lastly, according to the best practice principles put forth by CIRIA (Woods Ballard *et al.*, 2015), a SuDS scheme should aim at enhancing local biodiversity through the introduction of a wide array of plant forms and species and, whenever possible, provide a range of different habitat such as ponds or forested areas. In turn, these newly created habitats attract insects, molluscs as well as birds, small mammals and amphibians.

The SuDS scheme of the Grey to Green was planned as a series of interconnected swale cells. Swales (also termed bio-swales or vegetated swales) are vegetated depressions that are primarily built for conveyance of surface water (City of Portland, 2006; Susdrain, 2012). However, as is the case with the Grey to Green scheme, check dams (Figure 2.4) can be added in order to slow down the flow further and encourage infiltration if the bottom of the swale is not sealed with concrete or other impermeable materials. Swales are also known to be efficient at removing suspended solids onto which a majority of pollutants are attached (Scholes *et al.*, 2005). This is of importance in the present case as the catchment area is the nearby road where, notably, oil residues from vehicles will be deposited (Bastien *et al*, 2010). The catchment area also includes the nearby footpath as well as two planting beds on West Bar. The latter are part of the Dry Planting elements but concerns about water infiltration to the basement of adjacent buildings pushed the architects to add outlet pipes routing the excess water away from these beds into the swale system. The soil chosen for this scheme was a sandy loam with a low amount of organic matter and mostly made from recycled elements (glass, compost, etc.) (see Table 2.1 for further details). The predominantly coarse aggregate medium was selected for its capacity to encourage infiltration.

Table 2.1: Mass fraction of various soil types entering in the composition of the growing medium used in the Grey to Green Scheme (Bradbury, D., *personal communication*).

Percentage by Mass	Description of component
50%	5 – 20 mm sandstone aggregate
25%	Crushed glass
15%	Composted green waste
10%	Sandy loam (with maximum 8% clay)

Figure 2.3: Details of the bio-swale elements that make up the SuDS scheme of the Grey to Green (Photographs by author).
A. Detail of the kerbside with the road being on the top right corner and the planted area being in the bottom left corner. The arrow points to the "porous shelf" designed to slow down the inflow from the road.
B. Close up of some check dams forming the boundaries of individual cells. There are pipes at the base of the dam that route the flow to the next cell if the water level rises. The notch in the middle is there in case the water level rises higher and the weir can act as a channel for surface flows.
C. Photograph of cells immediately after the growing medium and the vegetation were installed. The uncut pierced outflow pipes can be seen covered in geotextile on the sides of each cells.

The flow is routed as follows. The rainfall falling on the swale and incoming runoff from the drained area will infiltrate (the rate of which is dependent on the medium's prior moisture content) and spread within a single cell. A porous shelf (see Figure 2.3A) was added between the edge of the road and the swale, its purpose is to provide a rough surface to slow down the runoff coming from the road. If the water table rises within a cell then it is collected by a perforated inlet pipe and routed into the flow control chamber. The water is then routed to the next cell and distributed along its width via a perforated outlet pipe (Figure 2.3C). If rainfall exceeds the outflow rate of the perforated outlet pipe and the rate of infiltration then ponding may occur. If the water level rises further, it will then pass through the notch into the next cell. If the water level continues to increase then it can flow over the weir. Lastly, each cell and check dam is lower than the road, hence if the system is saturated then the swale will just act as a conveyance channel and this should prevent the road from flooding. At the end of the swale there are two grills. The first one leads to an outlet in the nearby River Don for regular outflow (pictures in Figure 2.5). In case of exceedance flow, another grill leads to the sewers. Figure 2.4 summarises the expected flow of water within a typical swale cell.

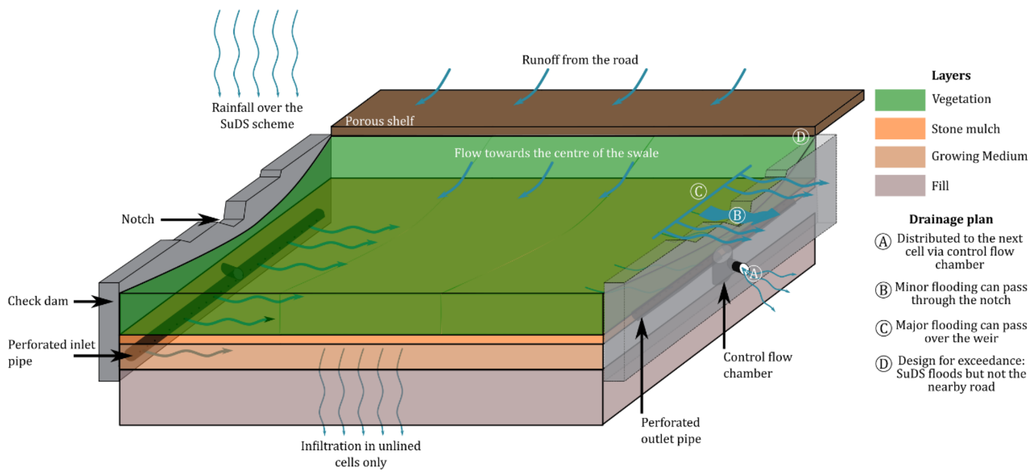


Figure 2.4: Schematic of an individual cell within the swale with an emphasis on the flow of water within the system (Author's work).

In terms of water quantity reduction, the system was designed as follows. It should handle the peak inflow of a 1 in a 100 years return storm event to which 30% of rainfall was added to take climate change into account. In this latter case, the outflow of the system should be 18 $l.s^{-1}$ (see Table 2.2 for comparison of the different outflow reductions) which is the maximum flow the outlet pipe to the River Don can handle. In case of exceedance (i.e. flows above 18 $l.s^{-1}$) the flow is then routed to the sewer system. Table 2.2 shows the predicted outflow reduction rendered possible thanks to the installation of the SuDS for three kinds of rainfall events. It must be noted that the simulation work undertaken by the Sheffield City Council was undertaken under the assumption that all cells were lined (Tudor and Nowel, 2016).

Table 2.2: Comparison of the predicted reduction by the SuDS scheme of the peak outflow volumes (Tudor, Z. Chief Landscape Architect, *personal communication*)		
Events	Built ($l.s^{-1}$)	SuDS ($l.s^{-1}$)
1:30 years, 60 minutes	80	9
1:100 year, 60 minutes	115	14
1:100 years + 30% (Climate Change), 60 minutes	150	18

The catchment area comprises the sidewalk on which the Grey to Green is installed and half of the lanes of the West Bar road (Bradbury, 2014). While the exact area for the catchment area could not be obtained, it can estimated as being between an equal to twice the area of the SuDS scheme itself. It can be argued that the design is overly conservative as the ratio of drainage area to drained surface is quite high, indeed the SuDS must drain only half of the width of the two lane road on West Bar and whichever flow comes out of the two additional planting beds. This conservative design choice has been justified by the Chief Landscape Architect who reported that due to the experimental nature of the scheme, they were ensuring that no failures would happen (Tudor, Z., *personal communication*). Indeed, a failure in the system could result in bad press and lower public acceptance, hence potentially discouraging further investment.

Lastly, the SuDS scheme aims to manage stormwater quality in addition to quantity. It is evident that all the flow that infiltrates to the grounds will not end up in the watercourse but the Grey to Green was designed to promote pollutant treatment. As shown in Figure 2.4, in a fashion not unsimilar to ponds, the last two swale cells on West Bar were lined with waterproof fabric to let water stagnate and encourage such processes as photo-degradation and microbial degradation (Environmental Agency, 2007).

Figure 2.5: Photographs highlighting how outflow is managed on the Grey to Green Scheme.
A. This cell, the last in the main stretch, was sealed with geotextile. **1** shows where a grill was installed to let the water flow out. Grill **1** is elevated to allow photolysis or bacterial degradation to depollute the stagnant water.
B. This is the last cell in the SuDS scheme which is located on Bridge Street. It is separated from the main stretch via an underground pipe. The outflow from **1** then remerges in **2** and spreads across the cell. If the flow is not absorbed then it will flow through **3**. This grill is connected to an outlet pipe to the nearby river Don. In case of exceedance flow, then the water will be also directed in **4**, a grill leading towards the sewers.

2.3.3 The planting

A major visual characteristic of the Grey to Green scheme is its unique, multi-layered, naturalistic urban meadow (illustrated in Figure 2.6). In the context of this research, an urban meadow (also shortened to meadow in this body of work) is understood as being different from natural grasslands (Joint Nature Conservation Committee, 2014) and different from traditional hay meadows (The Royal Society for the Protection of Birds, 2017). While the former is a natural grassland that is entirely natural, the latter is a semi-natural ecosystem that is affected by low intensity grazing or an annual cutting to produce hay for livestock. Depending on the specific soil conditions, altitude and level of management these different types of grass-dominated ecosystem may be more or less species rich. The urban meadow, on the other hand, is a meadow-like community which was constructed or managed to be fit for an urban context (Mårtensson, 2017). Urban meadows have the goal of having high grass and forbs diversity which supports a higher number of birds and invertebrate life forms but are also meant as a landscape for human interactions.

Naturalistic or informal planting is understood here as a more random-looking and natural-looking type of design. It is opposed to traditional designed planting that is usually undertaken by the landscape architect profession where species or groups of individuals are placed individually in order to produce a certain effect or have a certain visual rendering, using a detailed planting plan. In the present case, the landscape architects devised various species' lists, according to the location but each individual or groups were not assigned a spatial location within individual planting beds. Hence, the naturalistic urban meadow is a species-rich community that is natural looking but not entirely disordered either. It has a high diversity of shapes, colours and size. It has an informal planting plan but it is not a wild landscape since the species were selected and grouped in communities. Lastly, it is managed, contrary to natural landscapes, once a year in winter, in contrast to hay meadows which are cut in summer.

The planting itself was undertaken half-cell per half-cell (axis along the outlet pipes) by construction workers who planted the individuals using the 'random planting' method. In the latter, contractor place individual plants randomly within an area to achieve a highly naturalistic effect (Dunnett and Hitchmough, 2004). In effect, instead of a planting plan, a set of instruction is used to guide this placement. For example, the plant mix comprises a stipulated percentage of each component species and the species are distributed according to this percentage. A stipulated planting density (typically 8 – 12 plants per m^2) enables plant spacing to be worked out. Adjacent cells were not planted by the same workers. There were, however, two constraints on plant installation. The first was the overall position of drought and wet tolerant species which had to be adapted to a SuDS or non-SuDS area and be appropriate to the expected level of drought within the SuDS. Indeed, the edge of the swale is expected to be much drier whereas the centre of the swale is expected to be regularly flooded, hence plants who can sustain either or both conditions should be placed in the appropriate area. The second was a design choice to still retain a pattern within the planting using a single species of grass. The tall growing grass *Calamagrostis x acutiflora 'Karl Foerster'* was planted in such a way as to create division of the space in the shape of a sinusoidal wave. The planting motif is used as a visual element to instil a sense of dynamism along the length of the SuDS scheme. Its high growth habit is put to contribution as well in order to visually have a clear divide with the road behind.

There are three main communities planted throughout the scheme. They are referred to as Dry, Semi-wet and Wet species mix. Each of these species mixes goes in parts of the Grey to Green scheme according to the expected amount of rainwater and whether the bed has a drainage function or not. Hence, areas which are not part of the SuDS scheme and are supposed to be well drained will remain drier throughout the year. Here, the diversity is maximised in these areas with 55 species planted (see Table 2.3).

The SuDS scheme is mostly planted with the semi-wet species mix. With 32 different species, the latter is supposed to be able to withstand high amount of water for short periods of time; time during which the excess runoff percolates down or is conveyed through the check dams and down the slope. Otherwise, it is expected that the swale will remain dry. A smaller portion of the SuDS is planted with the Wet species mix (at the bottom of West Bar towards Bridge Street in Figure 2.1 and 2.2). This community is the least diverse with fourteen different species, some of which overlap with the Semi-Wet mix (see Table 2.3). This community has been put together with the expectation that the swale in this area will receive a lot more inflow, might pond at times and overall be more humid. Indeed, it has been installed at the connection with Bridge Street where there is a strong inclination and hence it is expected that more water will converge towards these areas.

In addition to these three aforementioned species mix, 9 evergreen species and 20 bulb species were introduced all across the planted areas. 5 type of trees were also planted in various places along the scheme. The complete list of species may be found in Table 2.3 below. In total, 40 trees, 45’000 bulbs, 665 evergreens and 26’000 herbaceous plants were planted on this 500 metres stretch (CEEQUAL, 2016).

Figure 2.6: Photographs of the vegetation on the Grey to Green (all from the author).
A. This one was taken shortly after the first annual cut which left the soil bare in a lot of places.
B. This one was taken about three weeks after A and shows the vegetation becoming greener and bushier with the first flowers (bulbs) appearing, taken in March.
C, D and **E**. These photos, taken towards the end of the summer of the second growing season, illustrate the diversity of geometric shapes, growth habits, heights and flower colours which gives rise to a space that is densely occupied both on and above ground as well as providing a strong visual interest.
F. In this photograph, the pattern created with *Calamasgrostis x acutiflora* is visible as an arc of a circle, this helps the eye to still find order and coherence within the landscape.

Table 2.3: Species lists per type of communities and other landscape features (Tudor, 2014)	
DRY SPECIES	**WET SPECIES**
Achillea filipendulina 'Coronation Gold'	Astrantia major claret
Achnatherum calamagrostis	Caltha palustris
Anelmanthele lessoniana	Cynogolssum amabile
Anemone japonica 'white'	Deschampsia 'Goldtau'
Armeria maritima	Geum 'Emory Quinn'
Aster amellus	Hemerocallis lilio asphodelus
Aster 'Purple Dome'	Iris robusta 'Gerald Darby'
Aster sedifolius Nanus	Juncus 'Carmens Grey'
Astilbe 'Purple Lance'	Lychnis flos cuculi 'White Robin'
Betonica officinalis	Lyhtrum salicaria 'Zigeunerblut'
Calamintha nepeta 'Blue Cloud'	Persicaria bistorta
Carex secta	Primula florindae
Centaurea montana 'Jordy'	Primula sikkimensis
Coreopsis verticillata 'grandiflora'	Veronicastrum v. 'Roseum'
Deschampsia 'Goldtau'	
Dianthus carthusionorum	**SEMI-WET SPECIES**
Echinacea pallida	Amsonia tabernaemontana salicifolia
Echinops ritro Veitchs Blue	Anelmantheie lessoniana
Erodium manavescii	Aster amelius
Eupatorium cannabinum 'Plena'	Astilbe 'Purple Lance'
Euphorbia polychroma	Betonica officinalis
Gaura lindeheimeri Whirling Butterflies	Calamintha nepeta 'Blue Cloud'
Geum 'Emory Quinn'	Carex secta
Helicotrichon sempervirens	Deschampsia 'Goldtau'
Hemerocallis lilio asphodelus	Echinacea pallida
Heuchera sanguinea	Eupatorium cannabinum 'Plena'
Iris robusta Gerald Darby	Euphorbia polychroma
Knautia macedonica 'Mars Midget'	Gaura lindheimeri 'Whirling Butterflies'
Kniphofia 'Tawney King'	Geum 'Emory Quinn'
Libertia formosa	Hemerocallis lilio asphodelus
Limonium latifolium	Heuchera sanguinea
Luzula nivea	Iris robusta 'Gerald Darby'
Lychnis coronaria	Iris sibirica 'Tropic Night'
Lychnis flos-cuculi	Juncus 'Carmens Grey'
Lychnis flos-cuculi 'White Robin'	Kniphofia 'Percy's Pride'
Lyhtrum salicaria 'Zigeunerblut'	Kniphofia 'Tawny King'
Malva moschata	Luzula nivea
Miscanthus sinensis 'Undine'	Lychnis flos cuculi 'White Robin'
Molinia 'Poul Petersen'	Lyhtrum saiicaria 'Zigeunerblut'
Origanum laevigatum 'Herrenhausen'	Molinia 'Poul Petersen'
Panicum 'Dallas Blues'	Miscanthus sinensis 'undine'
Perovskia atriplicifolia	Polemonium caeruieum
Polemonium caeruleum	Primula florindae
Pulsalilla vulgaris	Rudbeckia fuigida deamii
Rudbeckia fulgida deamii	Salvia X sylvestris 'Mainacht'
Salvia nemorosa 'Carradonna'	Sanguisorba Red Thunder
Sanguisorba 'Red Thunder'	Succisa pratensis
Saponaria 'Max Freil'	Veronicastrum v. 'Roseum'
Scabiosa columbaria	
Sedum 'Jose Aubergine'	**BULBS**
Stachys byzantina Big Ears	Allium aflatunense
Stipa gigantea	Allium sphaerocephalon
Succisa pratensis	Allium stipitatum 'Mount Everest'
Verbena bonariensis	Camassia Leichtlinii Alba

Veronicastrum v. 'Roseum'	Camassia Leichtlinii caerulea
	Camassia quamash
EVERGREEN STRUCTURE PLANTING	Eremurus Bungei
Artemisia arborescens 'Powis castle'	Eremurus Cleopatra
Cornus kousa 'China Girl'	Eremurus robustus
Euonymus alatus 'Compactus'	Fritillaria imperialis Lutea
Phlomis tuberosa ’Amazone'	Fritillaria imperialis Rubra maxima
Pinus Mugo 'Mops'	Galtonia candicans
Rosemarinus o. 'Miss Jessops upright'	Galtonia viridiflora
Sacoccocca hookeriana 'Digyna'	Gladiolus communis byza ntinus
Viburnum plicatum 'Mariesii'	Lilium martagon 'Orange Marmalad'
Yucca flaccida 'Ivory’	Lilium martagon 'Russian Morning'
	Nectaroscordum siculum bulgaricum
SPECIMEN TREES	Nerine bowdenii
Gleditsia triacanthos 'Skyline'	Ornithogalum magnum
Quercus palustris	Tulipa sylvestris
Cercis sliquatrum	
MULTI-STEMMED TREES	**GRASS CHAIN STRUCTURE**
Euonymus alatus or Betual pendula	Calamagrostis x acutiflora 'Karl Foerster'
Betula pendula	
Cercis sliquastrum	**ADDITIONAL GAP PLANTING**
	Ameria maritima

2.3.4 Development and economic opportunity

When the City Council deemed a portion of a highway to be redundant after the construction of the inner ring road in 2007, it saw the opportunity to reshape it to a dual purpose: economic redevelopment and flood management (Sheffield News Room, 2015b). Indeed, the City Council believes Sheffield must simultaneously engage with a prosperity gap of £1.6 billion and protect itself from massive floods like the ones that occurred in 2007 (Sheffield City Council, 2013).

The total budget for Phase 1 of the Grey to Green scheme amounts to £3,696,904 (£3.7 million) (Department of Landscape, 2016). The main funder of this scheme is the Sheffield City Region Investment Fund (SCRIF). This fund is primarily concerned with economically galvanising various part of the Sheffield area (Sheffield City Region, 2016). One of the main aims of the Grey to Green scheme is therefore to provide a setting to attract companies and investors, encourage real estate redevelopment and hence create employment, whether directly or not. On this note, the City Council predicted the creation of around 1,900 jobs following the redevelopment of the area surrounding of the Grey to Green (Sheffield City Council, 2015b). This is not the first project of its kind in Sheffield where green infrastructure is used as a means to improve social and economic well-being. Indeed, such an endeavour has been pursued on the Manor and Green Estates in order to revitalise a large area of neglected open green space (Commission for Architecture and the Built Environment, 2009).

The second main source of fund comes from the European Regional Development Fund (ERDF). This is a scheme set up by the European Union to support economic, social or environmental projects in regions that suffer from a gap in their development (Eur-Lex, 2010). The Grey to Green scheme complies with the requirements of these funds as it is notably intended to not only promote environmental benefits through water management but also attract investors into the area in order to foster employment.

2.3.5 Art display

Once construction had started, the City Council realised it had made some savings in comparison to the budgeted amount for the endeavour (Sheffield City Council, 2015c). Indeed, the deal with the construction contractor, North Midlands (Built Environment Hub, 2015), turned out to be less costly than envisaged. The council had originally allocated £50k for the art bid but found themselves with a £110k surplus. With a total £160k left, the Council decided, in agreement with its funders, to make an invitation to tender for the creation of art features (Ogden, 2015).

It is interesting to note, in this regard, that a local cycling campaign body (the "Cycling Forum") made a Freedom of Information request to the Council desiring to see the economic report. Following this, they campaigned for the budget to be used to build cycling tracks instead of public art (Beardmore, 2015b). After the final vote regarding the allocation of the budget was postponed, the City Council eventually decided to pursue the art bid. This situation could represent a stakeholder's conflict of interest. The money dedicated to the art could indeed have been channelled for the construction of cycling paths. However, in Ogden's report (2015), it is clearly mentioned that the overall design of the scheme would have had to change if it were to include separate cycling paths and due to funding deadline, the project needed to go ahead without modification of the design. The report also mentions that the potential cycling and walking conflict had already been previously noted and dealt with by the appropriate representing bodies.

Figure 2.7: One of the five art totems installed along Phase 1 of the Grey to Green.

There are five "totems" that are displayed along Phase 1 of the Grey to Green. They are four metres high and the original design came from Sheffield City Council Design Team (Sheffield City Council, 2015b). They are made of steel brightly coloured boxes that are stacked together. Within some boxes, there are stone carvings with representations or illustrations of historical events or local stories. Some other boxes are hollow. The totems are accompanied by information boards alongside to aid the public's interpretation of the art display.

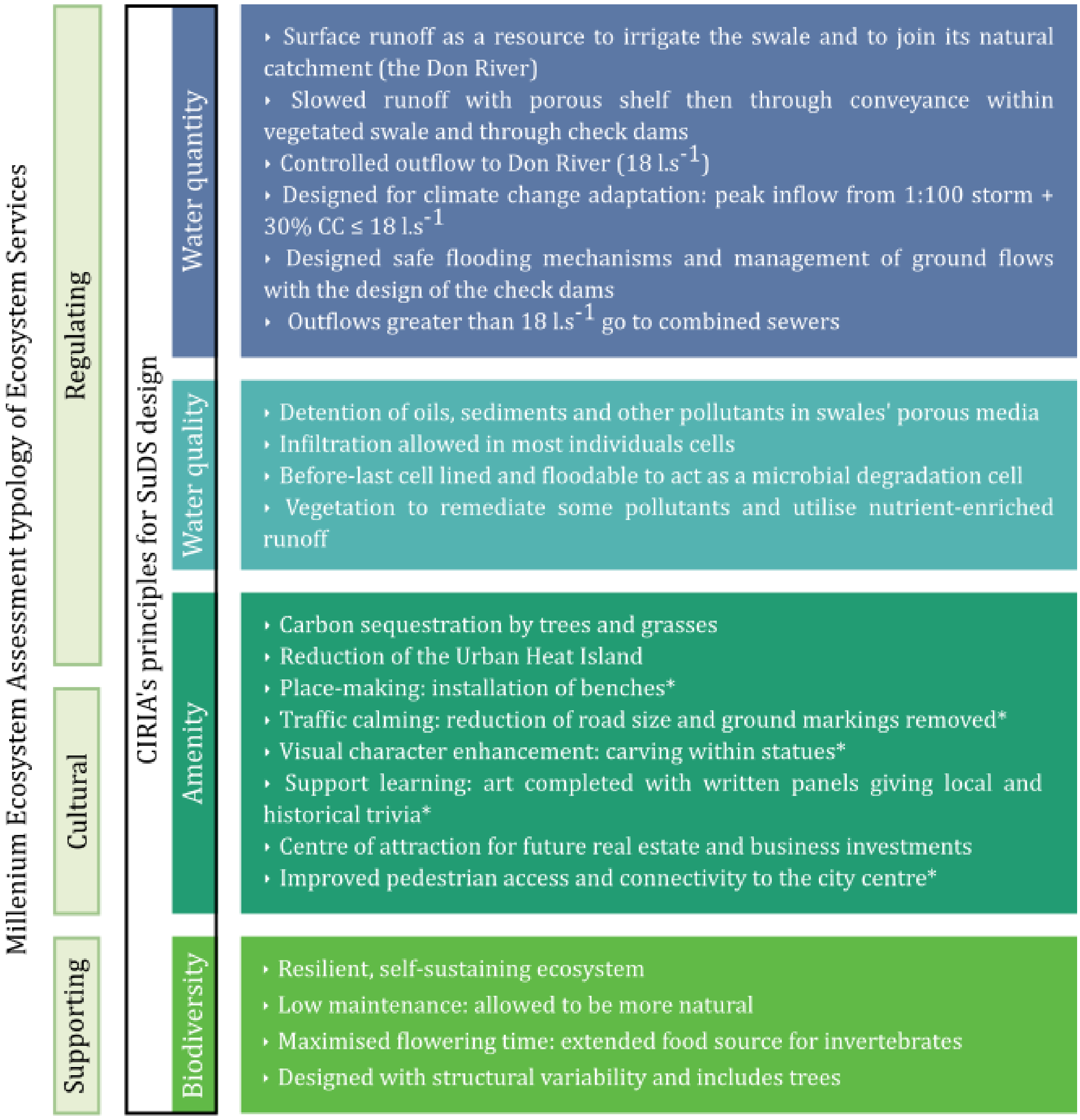
2.4 Greenways and ecosystem services

As the previous description has highlighted, this scheme contains a plethora of elements, incentives and design characteristics. In Searns' (1995) classification, the Grey to Green would be a Generation 3 greenway. He describes such schemes as:

> "emerging 'multi-objective' greenways that address needs of wildlife, flood damage reduction, water quality, education and other infrastructure needs in addition to urban beautification and recreation" (p66).

In other words, these new types of Green Infrastructure serve a purpose not only as a source of recreation (in the form of walking or offering space for seating) to its users (Gobster, 1995) but as a means to provide ecological services and most notably sustainable flood risk reduction.

The Grey to Green fulfils a number of CIRIA's recommended guidelines for SuDS (Woods Ballard *et al.*, 2015, pp 33-34) that are regrouped in four main objectives: water quality improvement, water quantity management, biodiversity support, and amenity creation. Yet a different way to examine the outputs of the Grey to Green is to use the Millennium Ecosystem Assessment's typology of ecosystem services (Millennium Ecosystem Assessment, 2005). Figure 2.8 summarises all the benefits (term used by CIRIA) and ecosystem services (term used by the Millennium Ecosystem Assessment). In Chapter 1, ecosystem services were defined as: the benefits (or the drawbacks) humans derive, directly or indirectly, from the existence, functioning and exploitation of ecosystems. In Figure 2.8, services marked by an asterisk cannot be considered as ecosystem services as per the definition used by this project but are counted as benefits per CIRIA's criteria. These benefits include facilitated pedestrian connectivity or art forms for example. These added benefits are more the result of the overall design of the scheme rather than the product of the function of the ecosystem it harbours. These benefits were nonetheless included here since the ecosystem itself could be seen as providing an aesthetically improved setting for these benefits to exist in. It was evident the Grey to Green, by design, was going to deliver numerous services. However, given the novelty of its features, the use of meadow vegetation notably, it was decided to gauge public's acceptance and perception of the scheme while studying how it affected the local microclimate and thermal comfort.



Notes:

* These cannot be understood as Ecosystem Services in the sense of the MEA, rather the scheme provides a context in which these services can be delivered.

‣ Other supporting services such as nutrient cycling are understood as being part of the normal functioning of the ecosystem, and the Grey to Green was not designed to maximise these supporting services, hence they are not mentionned in this table.

Figure 2.8: Summary of ecosystem services, as defined by the Millennium Ecosystem Assessment, and the overlap with CIRIA's objectives for SuDS schemes delivered by the Grey to Green scheme.

Chapter 3: Naturalistic meadows enhance aesthetics and perception of streetscape

3.1 Introduction

The Grey to Green, introduced in the previous chapter, is a multi-purpose vegetated area planted with a naturalistic flowering meadow meant to deliver regulating and supporting ecosystems services. The vegetation possess characteristics which depart from usual urban green spaces such as a lack of a formal planting plan and lack of cutting through the growing season and it was unclear whether dwellers would accept it and benefit from its presence or not. Hence, the aim of this chapter is to evaluate the delivery of some cultural ecosystem services that stem from proximity with the scheme and particularly its meadow-dominated vegetation. To do this, two dimensions will be explored: the acceptance of the planting and the perception of this newly redesigned space.

3.2 Urban green infrastructure and ecosystem services

Urban green infrastructure (UGI) has the potential to simultaneously deliver many ecosystem services: for example surface water management (Digman *et al.*, 2012), climate change adaptation (Derkzen, van Teeffelen, & Verburg, 2017) or human well-being Grahn & Stigsdotter, 2003, Riechers, Barkmann and Tscharntke, 2016). The efficient functioning of UGI is at least partly dependent on the content, diversity, spatial arrangement and layering of the vegetation, and there is increasing evidence that vegetation that is more diverse and contains a greater variety of plant functional types, is more effective than simple, low diversity vegetation (e.g Lundholm *et al.*, 2010, Yuan & Dunnett, 2017). This is in-line with ecological theory that suggests that diversity of plant species may positively influence such ecosystem properties as overall productivity, or resistance to external stresses and disturbance (Tilman & Lehman, 2002). Conversely, typical designed urban vegetation tends to be very simple in its species composition, and is intensively maintained to promote a neat and tidy appearance, with frequent maintenance, irrigation and chemical inputs. Advocates of a more sustainable approach to integrating ecologically-functioning vegetation into UGI propose systems with greater species diversity, and a less intensive (extensive) maintenance regime (Breuste, 2004;

Garbuzov *et al.*, 2013). In many countries, the context of dwindling public funds for intensive maintenance of urban green spaces has also led to the need to actively consider less intensive practices (Jorgensen *et al.*, 2002; Southon *et al.*, 2017). Almost by definition, a more sustainable, extensive approach to urban greening results in a greater naturalistic and less formal character to the vegetation (Hitchmough & Dunnett, 2003).

A key objective for UGI application is to reduce the total area of impervious, water-shedding sealed surface, with soil-plant systems that enhance sustainable stormwater management and promote a wide range of other ecosystem services (Gill et al, 2007). Comprehensive greening in high-density urban environments has been the subject of relatively little research (Jim & Chen, 2003), and yet in these contexts the extent and proportion of sealed surfaces is at its highest. Population and land-use pressure mean that opportunities for significant conventional greenspace (large-scale parks and gardens) can be limited (Gill et al, 2007; Ng et al, 2012). Therefore innovative elements such as green roofs and green streets become important means for integrating UGI into areas where other opportunities are limited (Gaffin et al, 2012). Road, travel surfaces and sidewalks constitute a significant proportion of urban imperviousness, and are perhaps the highest contributor to urban water runoff pollution (EPA, 2008). Green streets apply UGI components to manage stormwater while maintaining the primary function of the street for vehicles, cyclists and pedestrians (Philadelphia Water Department, 2014). Components of green streets may include street trees, street-side planters, permeable paving, rain gardens (EPA 2008), but are largely composed of bioswales integrated into the streetscape (Church 2015).

Extensive application of such components in green streets can add significant aesthetic value and biodiversity into areas that would otherwise be devoid of vegetation (Steiner & Domm, 2012). However, the majority of urban bio-retention features implemented to date are dominated by vegetation with low species richness, potentially leading to adverse visual effects and poor interaction with local biodiversity (Dunnett and Clayden, 2007). Despite being highly engineered features, the vegetation component is also usually the most visible aspect of bioswales and rain gardens, and therefore the content, and structural and visual characteristics of that vegetation will, in large part, determine public perceptions regarding acceptability and understanding (Church 2015). As an alternative to standard low-diversity mixes of sedges and grasses, highly diverse naturalistic mixes of perennials (particularly flowering forbs and ornamental grasses) in meadow-like combinations have been proposed as a cost-effective, visually attractive and sustainable vegetation type for urban bioswales (Johnston, 2011; Hitchmough & Wagner, 2013).

3.3 Aim and objectives

It is now established that meadow vegetation may offer a variety of ecosystem services (supporting and regulating). It has long been recognised that there may be conflicts between ecological or environmental sustainability goals, and what users will accept, prefer and deem fit (for example Nassauer, 1995 and Breuste, 2004). In another words, there may be conflicts between cultural services and regulating/supporting services, as summarised in Figure 3.1. Because naturalistic planting styles have a very different visual appearance to conventional urban landscape, there is concern that people may not respond positively to these sustainable vegetation types (Ozguner and Kendle, 2006). What may be accepted as natural in wildland and agricultural landscapes may not be tolerated in high density urban contexts, where a degree of control, neatness and human intervention might be expected (Gobster *et al.*, 2007, Zheng *et al*., 2011). For example, Everett (2016) reported on the difficulty for residents of Portland to accept the appearance and plant choices of bioswales, even though they had been put in place as part of a larger flood risk management scheme.

There is encouraging evidence that urban meadows may be well received by its users. Previous studies in low-medium density urban and suburban greenspaces have indicated a public preference for biodiverse meadows over traditional herbaceous borders, bedding plants and lawns (Southon *et al.*, 2017). High diversity and abundant flowering content appear to be important in public preference (Jorgensen *et al.*, 2002; Lindemann-Matthies and Bose, 2007; Southon *et al*., 2017) in these contexts. To date, however, no studies have investigated public response to such vegetation when introduced in highly urban non-greenspace contexts, as part of a green street initiative. This work was intended, primarily, at addressing the gap of knowledge regarding the acceptance of naturalistic meadow-dominated green spaces within a highly urbanised context. To do so, the first objective of the study was to record *in situ* public attitudes and reaction towards the appropriateness and acceptability of meadow-like vegetation in an innovative green street initiative in the UK.

The second major aim of this study, as shown in Figure 3.1, was to probe if the urban meadow vegetation, as an instance of "nature", could provide cultural ecosystem services that would further liveability goals and promote human health. Indeed, cultural ecosystem services could be described as the intangible outputs of a biological community that promote human psychological and social well-being (Milcu *et al.*, 2013). To test for the provision of these services, questions relating to the improvement of perceptual qualities of the street environment were added. Four dimensions were chosen as part of this study. The aesthetic value of a street was the first. Positive evaluation of one's urban environment has been linked to promote liveability and quality of life, notably through promotion of walking behaviour (Forsyth *et al.*, 2008; Koohsari, Karakiewicz and Kaczynski, 2013). Derkzen, van Teeffelen, & Verburg's (2017) have demonstrated that urban green infrastructure was often viewed as positive for its association with air purification. It was unknown if this view was associated with meadow vegetation or not and as such was the second perceptual dimension probed for. Perceiving oneself as safe or not may be influenced by the presence and arrangement of vegetation (Ulrich, 1993; Jorgensen, Hitchmough, & Calvert, 2002). To probe the safety dimension, questions related to personal security and safety from cars were added to the questionnaire. The last dimension was the effect of vegetation on mood. Contact with instances of Nature has the faculty to uplift human mood and also restore fatigued cognitive processes (Hartig *et al.*, 2003). These are but a few dimensions of the cultural ecosystem services that green spaces may provide. These perceptual qualities, linked to the appreciation of the vegetation itself, may contribute to health promoting measures such as place attachment, walking and recovery of cognitive functions which, in turn, have strong social and psychological benefits. Hence, such perceptual dimensions were deemed critical in contributing to the feeling of liveability of a city.

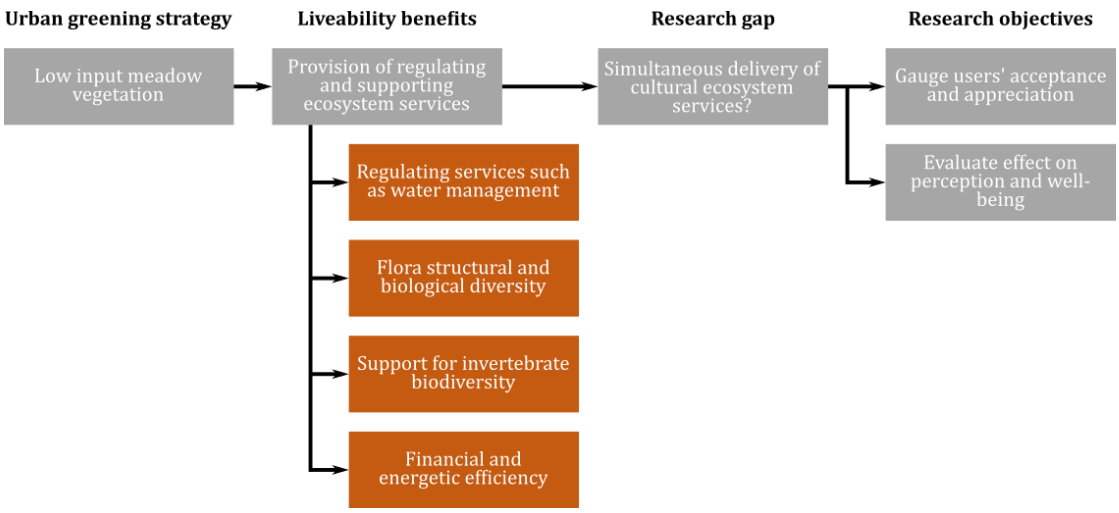


Figure 3.1: Conceptual diagram of the present study's rationale.

3.4 Methods

3.4.1 Questionnaire design

Many landscape perception studies use photo-elicitation techniques whereby respondents are shown real or manipulated images, and asked questions relating to those images (in Southon *et al*, 2016, for example). Because the Grey to Green scheme contains heavily used side-walks that are bounded on both sides by the new vegetation, it was decided to speak with users directly on site, and to obtain their impressions of the scheme as delivered, in its context. A questionnaire was developed (see Appendix 1) that, with some exceptions, was based on a series of statements that respondents were asked to agree or disagree with, using a Likert-scale (5 points) from "Totally disagree" to "Totally agree". The answers were coded from "-2" for total disagreement to "+2" for full agreement with a statement. To assess whether or not the Grey to Green had produced a positive change in people's opinion of the street environment, it was decided to pose questions with a positive bias. The null hypothesis is then that if the Grey to Green had failed to bring meaningful cultural ecosystem services, or even possibly deliver cultural disservices, then respondents would manifest their disapproval to positive statements and hence the items would have negative, zero included, scores. Since this survey was meant to be held in the street, within a busy environment, it was deemed necessary to produce as short of a questionnaire as possible; tailored for respondents who would potentially have little time to spare. In this manner, some of the factors intervening in aesthetic appreciation and perception of a landscape may not be covered but at least a short questionnaire made it easier for them to be completed and thus give a coherent data set for analysis. This questionnaire received explicit ethical approval as part of the overall Ethics Review mentioned in the first chapter.

Firstly, information about gender, age category, frequency of passage and reason to be on site were recorded. These pieces of information were designed to categorise the kind of people passing or stopping by the scheme. Then the survey dealt with the reaction to the planting and was aimed at gauging the acceptability of the naturalistic of the meadow. Four questions were asked in this category which were based on a previous large scale study on people's opinion on parks' planted areas (Hoyle, 2015). The respondents were thus asked whether they deemed the planting attractive, natural-looking, well maintained and fitting in its environment. These two last items were added in the questionnaire as qualitative research on UGI has shown these two dimensions have a strong impact on residents' opinion (Church, 2015; Everett *et al.*, 2015 for example). An additional closed question asked: "Would you like to see more of this type of greening around Sheffield?" This item was meant to probe if the planting was appreciated sufficiently to be deemed repeatable elsewhere and hence some insight into the faculty of meadow-like vegetation to become a socially acceptable and desirable landscaping norm.

Then questions related to respondents' perception of their urban environments were asked. Aesthetic appreciation of a landscape is one stepping stone towards proving the delivery cultural ecosystem services but it needed to be completed with items asking directly about them. The constraint of interviewing length was also taken into account in this section and only five items were retained. As introduced earlier, the respondents were probed on the following items: improvement of the overall street's aesthetics, personal safety (following Jorgensen, Hitchmough, & Calvert, 2002), decreased danger from traffic and improvement of air quality. The improvement of respondent's mood was also added. Following other research projects such as Hartig *et al.* (2003) and Marselle *et al.* (2014), the improvement of "happiness" was treated as a single item, as opposed to a composite score of multiple items. In this study, stating an improvement of happiness was seen as a measurable outcome of an overall positive affect brought by the scheme. In addition to the aforementioned items, respondents were asked, via a closed question, if they had changed their journey to pass by or through this area or not. This question was added under the assumption that if a greened area was deemed pleasant enough then it was expected that pedestrian traffic would increase in this portion, as was the case with treed streets in London (Sarkar *et al.*, 2015).

3.4.2 Sampling procedure

Prior counting undertaken by the University of Sheffield estimated a daily passage of 2000 to 3000 passersby in the area surrounding the Grey to Green (Dunnett, N., *personal communications*). For a confidence interval of 5% and a confidence level of 95%, the representative sample size is situated between 322 and 341 people. To ensure adequate representation of the passersby, three time periods were used (similar to the RUROS study, Nikolopoulou, 2004): 8:00 to 11:59; 12:00 to 14:59; 15:00 to 19:00. Preliminary information about the site indicated it was situated in a business oriented area, hence had an assumed higher frequentation during weekdays and working hours. However, weekdays and weekends were both sampled to ensure the study did not overlook any potential sub-group of users. The lead author and two interviewers participated in the street survey with a defined text to introduce the survey. Oral agreement to answer the questionnaire and to participate in the research were sought for each respondent. All analyses were performed using IBM's SPSS 23 software.

3.5 Results

3.5.1 Sample description

339 questionnaires were obtained over a period of ten non-consecutive days during the months of July and August 2016, with weekdays and weekends both being sampled for adequate user representation. The sample comprised nearly as many men as women (n = 169 and 170 respectively) and the most represented age groups were the 26 to 35 years old (n = 105) and 36 to 45 years old (n= 86) (see Table 3.1). These results are coherent with a sampling that occurred around a business district and thus can be seen as representative of an active population. While efforts were made to cover equally all time periods of the day, response rates varied greatly. The maximum number of responses were obtained in the middle of the day (12:00 to 14:59; n = 144) which is consistent with respondents having time to spare over their lunch breaks. In the same vein, frequentation of the area drastically fell past 17:30, once workers had left their office.

Table 3.1: Characteristics of the sample and distribution of responses

Sex		Age groups		Time period		Reason to be on site	
Male	169	18 - 25	74	Morning	88	For work	183
Female	170	26 - 35	105	Mid-day	144	For leisure	70
		36 – 45	86	Afternoon	107	On an errand	52
		46 – 55	51			To visit the site	34
		56+	23	Week-day	241		
				Week-end	98		
Total amount of questionnaires						339	

3.5.2 Reaction to the planting

Overall, the results (shown in Figure 3.2) indicated a very positive response to the planting intervention. For the reaction to the planting questions, mean scores indicated a positive appreciation of the scheme by being superior to 1 on a maximum of 2 except for the perception of maintenance. Planting attractiveness has the highest mean score (noted $\bar{x}$ henceforth) with $\bar{x}$ = 1.26, followed by the rating of the planting's character with $\bar{x}$ = 1.1. Despite the novelty of this type of scheme, naturalness received a high rating as well ($\bar{x}$ = 1.02). The lowest score, yet positive response, comes from the perception of the maintenance of the site with $\bar{x}$ = 0.88; the latter might, however, be indicative of a response to the less tended aspect of the vegetation rather than issues of littering or improper plant care. A Wilcoxon Signed Rank test confirmed that all aforementioned scores were positive. Indeed, responses were tested against the null hypothesis that if the planting had not elicited any positive reaction then the median response should be centred on 0. Unsurprisingly, all medians were significantly different from 0 ($p < 0.05$, median scores shown Figure 3.2) and were positive, thus indicating an overall positive reaction to planting. An additional binary question completes this set of appreciation scores. When asked if they would like to see more of this type of greening intervention in Sheffield, 98.2% of respondents responded positively (Figure 3.3). This suggests the scheme's perceptual qualities were appreciated and recognised as something that could be replicated elsewhere in the city

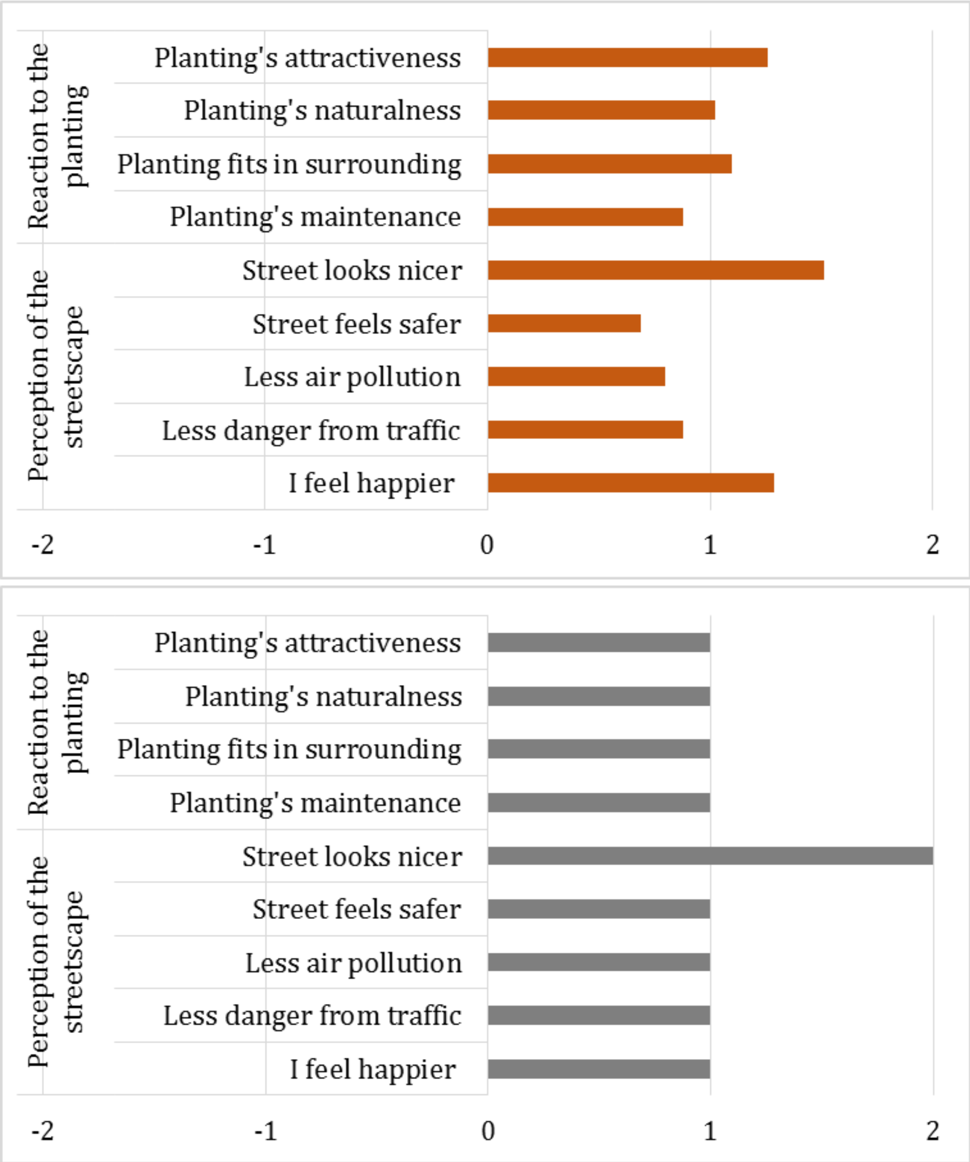


Figure 3.2: Mean (orange) and median (grey) scores for each of the 5-point items of the questionnaire. Each score is comprised between "-2" which would have the respond totally disagree with the statement and "2" which would have the respondent totally agreeing with the statement.

Following a Shapiro Wilk test ($p < 0.01$ for all items), parametric tests were applied to the whole data set as stipulated for items having a non-normal distribution. The effect of gender on the responses was measured using the Mann-Whitney test. The responses to the closed question returned no significant difference between sexes. The planting's attractiveness did not either, thought it was close to significance ($p = 0.073$) which contrasts which the other three items. Men and women rated differently the naturalness, the character and the maintenance of the vegetation ($p < 0.05$, see Supplementary Table 3.1 for full details). In all three instances, women's ratings were higher than men's. These result are coherent with other studies reporting gender asymmetry on landscape preference scores. In the case of the Grey to Green, the scheme relies heavily on flowering forbs for visual effects, a feature that women are expected to appreciate more (Jorgensen, Hitchmough, & Calvert, 2002). The effect of age on responses was tested via Spearman's Rank-Order Correlation. No associations were found between age and responses to the item related to the planting intervention.

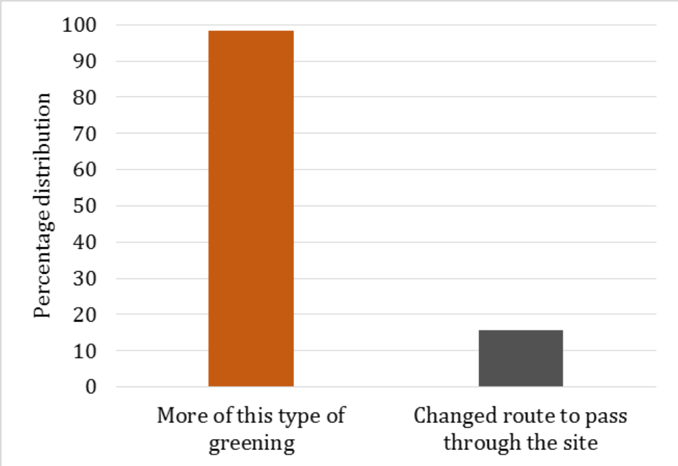


Figure 3.3: Percentage distribution of responses to the two closed questions.

3.5.3 Changes in perception of the urban environment

The reported change in perception of the urban environment were also largely positive (Figure 3.2). The aesthetic improvement of the streetscape has the highest mean, $\bar{x} = 1.51$, followed by an improvement of the mood, $\bar{x} = 1.29$. The perceptions of safety, lessened danger from traffic and a decrease in air pollution all have an average score between 0.5 and 1, indicating positive but more moderated responses (see Figure 3.2). Additionally, a binary question asking if respondents had changed their route to pass through the site indicated that 15.6% - roughly 1 in 7 persons - of respondents had done so (Figure 3.3). An increase in passage is, if anything, a testimony to people's appreciation of the scheme and coherent with the improvement of the perceptual qualities of the streetscape. Each answer was tested against the null hypothesis that if the greening intervention had had no effect then the median score would be 0. Once again, all items had a median significantly different from 0 ($p < 0.05$, median rating shown in Figure 3.2) as highlighted by a Wilcoxon Signed Rank test. This reinforces the conclusion that the overall design had had a beneficial effect on people's perception of their immediate environment. Men and women did not answer significantly differently on any of the perception items according to a Mann-Whitney test. However, women reported feeling happier than men ($p < 0.05$) having a score of 1.38 compared to 1.2 for men. This could be explained, partially at least, by the higher ratings women gave to the perception of the scheme. A Spearman's Rank-Order Correlation test showed no associations between age and responses.

An additional Spearman Rank Order Correlation test was undertaken to determine which factors correlated with the item "happier". All the items related to the planting and to the perception of the urban environment positively correlated with happiness ($p < 0.01$). This result underlines the conjunction of the appreciation of the landscape, improved urban environment and the intangible benefits human derive from these elements.

3.6 Discussion

Following an in-situ questionnaire probing for appreciation of an urban meadow-dominated green space and four perceptual qualities of the retrofitted space, results indicated that the scheme's aesthetic value was its most appreciated feature, which was not expected given the centrality of the location and the economic purpose of the area. Zheng, Zhang and Chen, (2011) and other authors have generally found that urban dwellers preferred neat, tidy and artificial landscape. It is interesting to note that the sample agreed with the fact that the planting looked "natural". This is surprising considering that its appearance significantly differs from more traditional form of greenery (urban parks using extensive areas of green turf for example) and departs significantly from the natural biotopes present around Sheffield such as the moorland and pastureland from the nearby countryside (Sheffield City Council Environmental Planning, 2011). However, the emphasis was put on adding flowering plants, species diversity and a random disposition of individuals, three features that have been proven to increase appreciation rating (Lindemann-Matthies, Junge and Matthies, 2010).

It was also noted that for a majority of the vegetation items, women rated the scheme higher than men. This may be explained by Kaplan's (1995) notion of compatibility between users' inclination and the aesthetic features of the vegetation. This means that women might have found within this landscape a lot more elements that they already preferred. Additionally, a higher prevalence of flowers may have driven women to giver higher scores to the scheme (Jorgensen, Hitchmough and Calvert, 2002). A most positive finding was that a naturalistic planting scheme may have its place within a business and commercial district which opens opportunities for landscape architects to incorporate urban meadows without fear of public rejection. This is strongly reinforced by the second highest score in the appreciation items: the planting's character. Through this item, respondents confirmed that they found the urban meadow as a fitting vegetation style within a highly urbanised and high profile street. However, an unavoidable limitation was the youth of the vegetation; having been installed for only a few months prior to the survey. As such, a lot of species had not reached their maximal height and cover. It is however assumed that people's perception of a mature community would not be less positive when in contact with a continuous meadow vegetation.

In parallel, perceptual qualities of the urban environment have improved as well. It seems that the scheme has, through traffic calming and footpath widening, rendered the street more appealing even though the scores are not as high as the ones related to its aesthetic dimension. A possible factor for this is the fact that people tend to feel safer in more formal landscape (Özgüner and Kendle, 2006). This informal characteristic of the scheme is also hypothesised to have brought down the rating of the perception of care (via the maintenance item). It is however encouraging that the rating are positive, this may represent a step towards attempting to find the compromise between a formal and a naturalistic landscape which each bring about similar but also diverging benefits to humans (Özgüner and Kendle, 2006).

This type of scheme improved the perceptual qualities of the street and more than 1 in 7 respondents reported changing their route to pass through the scheme strongly suggests that this form of GI has the potential to encourage walking behaviour. As contended by Sarkar *et al*. (2015), the promotion of an active lifestyle through walking includes improving the urban network by adding urban greenery rather than adding destination points. The high perception scores, augmented by a reported increased happiness are indicative of the potential of the scheme to increase psychological well-being through a reduction of stress (Grahn and Stigsdotter, 2003) or exercise of soft fascination which in turns reduces the attention load and allows restoration (Kaplan, 1995). This is direct evidence that even on a smaller scale (total length of the scheme at present is around 500 metres), a meadow-dominated bioswales scheme may have a positive impact on mental health, a finding also reported in Peschardt, Stigsdotter, & Schipperrijn (2016).

3.7 Conclusion

This chapter sought to understand if urban meadow vegetation could deliver cultural ecosystem services in a city centre context. As is the case with the study site, urban meadow vegetation can be designed to require low financial and maintenance input. If designed to have a high biodiversity it makes this type of vegetation it a sustainable choice for urban green infrastructure. An additional choice was made by the designers of the Grey to Green which was to adopt a naturalistic planting style. This meant that although species list were established, the specific location of each plant was not predetermined. These various choices have a clear aesthetic impact: high plant diversity, prevalence of flowers and messier appearance. The objectives of this chapter was thus to gauge users' acceptance of such aesthetic features and then evaluate the possible benefits users may derive from the transaction with this green space. It was noted that user adhesion to the scheme was high which contradicts theoretical views that were held towards messy ecosystems within urbanised areas. It was noted that the perception of the streetscape was also improved due to the scheme's presence. Transaction with the scheme also resulted in a clear improvement of the positive affect. These results suggest that the urban naturalistic meadow vegetation delivers cultural ecosystem services. Indeed, they fulfil higher order needs that ultimately translates into an increase in "happiness"; the scheme thus contributed to the liveability of this part of the city centre. Given the positive results, the quasi-unanimous desire to see more of this type of greening opens up the possibility for designers to include more frequently schemes with similar characteristics and pave the way towards a norm of UGI that is both optimised for environmental sustainability and human psychological needs.

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Supplementary Material

Supplementary Table 3.1: descriptive statistics, Mann-Whitney and Spearman's correlation results testing for rating differences as a function of sex and age respectively (n = 339), asterisk denotes significance at $p < 0.05$.

Items	Mean (Std deviation)	Mann –Whitney U value (p value)	Spearman correlation Rho value (p value)
Planting attractiveness	1.26 (0.679)	12931 (0.073)	0.049 (0.372)
Planting naturalness	1.02 (0.828)	12741 (0.047)*	0.030 (0.578)
Planting's character	1.10 (0.737)	12130 (0.007)*	0.024 (0.658)
Planting's maintenance	0.88 (0.814)	12345 (0.14)*	-0.007 (0.897)
Street looks nicer	1.51 (0.650)	12688 (0.032)*	-0.008 (0.884)
Street feels safer	0.69 (0.782)	14188 (0.832)	-0.013 (0.817)
Less danger from traffic	0.88 (0.847)	13664 (0.408)	-0.053 (0.329)
Less air pollution	0.80 (0.780)	13371 (0.236)	0.009 (0.874)
I feel happier	1.29 (0.660)	12446 (0.018)*	0.009 (0.872)
More of this space	Yes: 98.2%, No: 1.8%		-0.018 (0.742)
Changed route	Yes: 15.6%, No: 84.4%		0.014 (0.791)

Supplementary Table 3.2: Spearman's Ranked Order test on the planting and perception items on the outcome item "Happier". An asterisks denotes significant correlation.

Items	Spearman's Rho value (p value)
Planting attractiveness	0.353 (< 0.001) *
Planting naturalness	0.252 (< 0.001) *
Planting's character	0.266 (< 0.001) *
Planting's maintenance	0.287 (< 0.001) *
Street looks nicer	0.347 (< 0.001) *
Street feels safer	0.222 (< 0.001) *
Less danger from traffic	0.216 (< 0.001) *
Less air pollution	0.367 (< 0.001) *

Chapter 4: Influence of aesthetic appreciation, happiness and physiological acclimatisation in the immediate perception of comfort

4.1 Introduction

The last chapter established the Grey to Green's capacity to deliver of cultural ecosystem services: appreciation of the landscape, aesthetic improvement and increase in positive affect are the three most prominent outputs observed. To further the study of the influence of aesthetics on human perception, this chapter looks at how the latter could influence thermal comfort. In order to do this, thermal comfort will be introduced, measurement and questionnaire based analyses will be used to look at how the sensation of thermal well-being is influenced by the landscape. As such the objectives of this chapter are the following:

- Introduce a thermal comfort conceptual framework
- Derive local thermal comfort indices
- Study the influence of the scheme's presence and other personal factors on the thermal well-being

4.2 From cultural to regulating ecosystem services

One of the crucial aspects of urban life is the capacity of a city to provide an environment which promotes good physical health (Tzoulas *et al.*, 2007). The latter may be achieved through a plethora of ways. Allowing dwellers to walk, as a basic form of moderate physical activity, or providing larger open spaces for more intense forms of exercise are such health promoting measures (Sarkar *et al.*, 2015). Controlling air pollution has important health consequences: chiefly avoiding respiratory illnesses and facilitating the use of outdoor spaces (Webster *et al.*, 2015). Climatic factors also play an important role both directly on health and on the range of outdoor activities available to city inhabitants (Matzarakis and Mayer, 1996). For instance, extreme temperatures prevent citizens from carrying routine or leisure tasks in the outdoor environment without being exposed to serious heat or cold stress (Katzschner, 2006). Beyond discomfort, heat stress has also been shown to dramatically increase mortality rates (Roth, 2013). Thus, when discussing the liveability of an urban environment, it is central to consider the notion of thermal comfort; this concept is fleshed out further in the next section.

Typically, cities, by their very organisation and nature, lead to a well-known persistent elevation of temperature within their boundaries, the Urban Heat Island (UHI) effect (Davies, Steadman and Oreszczyn, 2008). The UHI has a direct impact on residents' thermal comfort and has important health consequences. Commonly, the UHI increases heat stress during the day and the continuation of this heat stress into a good part of the night means that sleeping schedules are also disturbed. Notwithstanding which global climate change scenario is examined, the common denominator is an overall increase in temperature (Jenkins *et al.*, 2010). It has been demonstrated that this would impact thermal comfort even more greatly than the change in air temperatures (Matzarakis and Amelung, 2008). It is thus crucial to mitigate these adverse aspects of urbanisation as they already negatively affect the lives of millions and climatic conditions are bound to deteriorate.

In Chapter 3, it was established that naturalistic meadow vegetation provided cultural ecosystem services. Through the appreciation of the aesthetic value and existence of a meadow, it was demonstrated that perceptual qualities of the urban environment was improved to varying degrees. So far, it may be said that naturalistic meadows contribute to the liveability of a city by fulfilling some higher order needs such as emotional and psychological well-being. However, the contribution to the fulfilment of more basic needs such as thermal comfort by said vegetation is unknown. In these regards, trees have already been considered and are known to provide relief, in most but not all cases, to thermal comfort through the provision of shade (Sanusi *et al.*, 2017) and transformation of sensible heat into latent heat (Erell, Pearlmutter and Williamson, 2011). The delivery of cultural ecosystem services, associated with their lower financial cost of maintenance and lower carbon footprint, makes meadow vegetation a suitable candidate to be integrated within new or existing green infrastructure. Grasses and forbs' climatic regulatory services has rarely been studied and given the extent of the impact of thermal comfort, the UHI and their consequences on human health, understanding their role on microclimate is of paramount importance.

4.3 Thermal Comfort Framework

4.3.1 Defining thermal comfort

Thermal comfort, sometimes referred to as human comfort, is defined by ANSI/ASHRAE standard 55 as the "condition of mind which expresses satisfaction with the thermal environment" (cited in de Dear and Brager, 1998). This interest in human comfort has mostly been framed in the context of building design and improvement of material property (de Dear and Brager, 1998; Nikolopoulou, Baker and Steemers, 2001). The research in this domain is concerned with optimising the occupant's level of comfort and providing liveable conditions throughout the year. There has been growing interest in transferring this concept of thermal comfort to outdoor situations (Honjo, 2009), most notably to provide urban dwellers with wider ranges of outdoor activities and increased liveability (Norton *et al.*, 2015). This has been however an uneasy transition as exterior parameters are much more prone to vary and the environment surrounding the dweller is much more diverse (structures and buildings, green areas, traffic etc.) than indoors (Smith and Levermore, 2008; Roth, 2013).

4.3.2 Establishing a framework

Previous research work has highlighted the sheer complexity of assessing outdoor thermal comfort (Chen and Ng, 2012). From choosing a comfort index, to the effects of vegetation and unravelling various psychological factors, understanding and measuring human outdoor thermal comfort is a complex endeavour (Lenzholzer, Klemm and Vasilikou, 2016). Prior work to theorise a framework for outdoor thermal comfort was notably conducted by Knez *et al*. (2009). The conceptual model they propose are a connection of how "place" acts in function of "mediators or moderators" to produce seven types of "human responses". While seemingly all-encompassing, their framework (Figure 1, p 103) foregoes the notion of time (or exposure) and bi-directionality of the relationship between the present experience with the sum of past experiences, expectations and preferences the past. The framework proposed here does not contradict Knez *et al.*'s (2009) work but rather simplifies it by enumerating all the factors, uncovered or predicted, of outdoor thermal comfort and attempts to group them coherently. Hence, based on a review of the recent literature, the Outdoor Thermal Comfort Framework is proposed. It is divided in three main mechanisms which are believed to act together at any time to produce the subject's assessment of their comfort (shown in Figure 4.1 below).

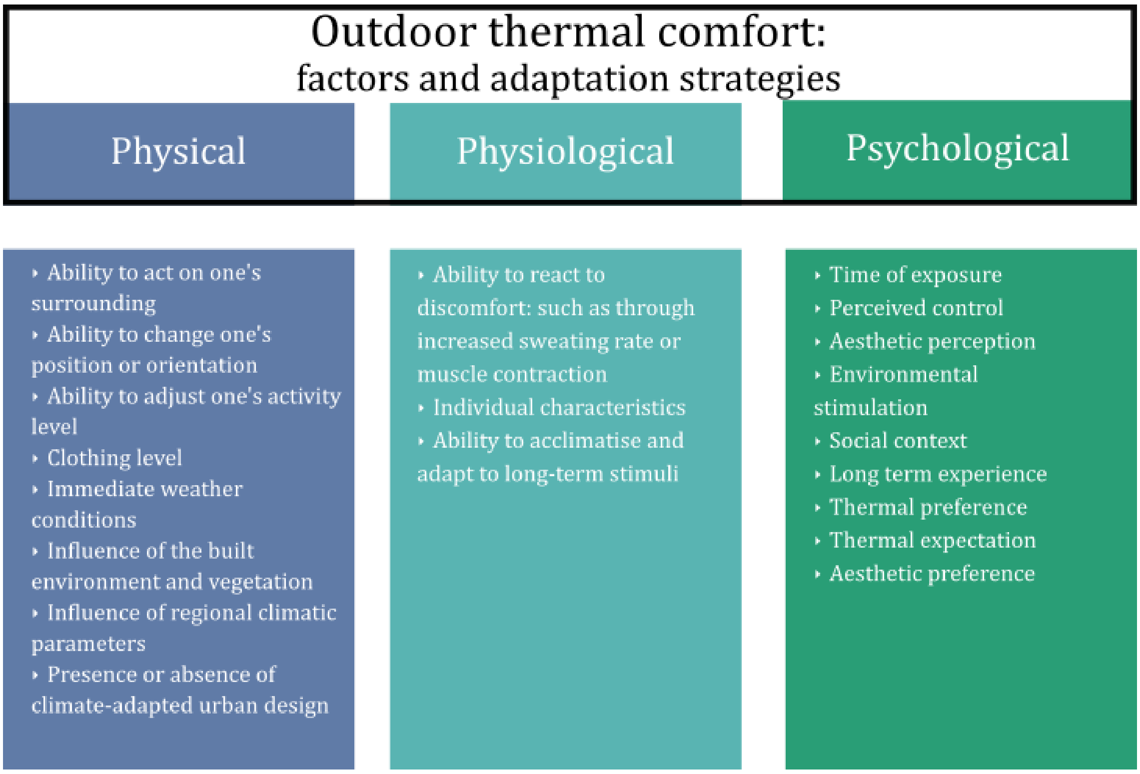


Figure 4.1: Outdoor thermal comfort framework as proposed and used in the present study. It lists the various physical, physiological and psychological components and adaptation strategies addressed in the literature.

4.3.3 Physical parameters

The sun's shortwave radiations (SWR) provide the necessary energy for climatic and living systems to exist on Earth. However, imbalances in the distribution of radiation occur. Some systematic imbalances happen due to the Earth's varying orbital distance to its star, its tilted axis and rotation on itself. Locally, imbalances may come from atmospheric conditions such as presence of clouds, gases and particles in suspension (Ramirez and Muñoz, 2012; Roth, 2013). This radiation provides the energy to create the climates, wind patterns, heat up the air and the surfaces and affect the vapour content in the air across the Earth and, in turn, large scale climates will affect atmospheric conditions at smaller scales.

At the micro-scale, defined by Erell, Pearlmutter and Williamson (2011) as the scale that goes from the centimetre to the kilometre, which is the one relevant to a pedestrian, the regional climatic patterns will influence the local weather as much as the three-dimensional environment surrounding a person; it may be opened or encased, within a natural or an urban environment among other properties. Within cities, the width and height of the streets (Erell, Pearlmutter and Williamson, 2011), the material used in the construction of the fabric (Ramirez and Muñoz, 2012) and the presence, or absence, of vegetation (Kleerekoper, van Esch and Salcedo, 2012) will significantly impact the radiative balance of the environment. Equally, the buildings can modify wind patterns, by emitting or absorbing radiation they will heat up the air beyond that of an equivalent vegetated area (a phenomenon termed the UHI) (Norton *et al.*, 2015). Vegetation may also alter the microclimate by shading the surface and buffer high winds and temperatures (Kleerekoper, van Esch and Salcedo, 2012) for example.

Physical parameters of the environment influence the microclimate which is itself the primary driver of outdoor thermal comfort (Matzarakis, 2012). Liu, Zhang and Deng (2016), for example, proved that the microclimate was the primary predictor of thermal comfort using a sample of around 7800 respondents in China. It is common practice to consider four parameters: solar radiation, wind speed, air temperature and humidity (Matzarakis and Mayer, 1996). Amongst the four microclimatic factors considered, it seems air temperature has the most impact. However, numerous studies have highlighted the seasonal and geographically variable nature of their relative contribution (Lin, 2009). In a major pan-European study led by Nikolopoulou (2004), each climatic factor had a different predictive weight according to which country was considered. Another study highlighted how wind speed may increase or decrease outdoor thermal comfort depending on the season and the specific urban setting a person is in, making it desirable or not (Trindade da Silva and Engel de Alvarez, 2015). Moreover, this interplay between the urban form and the micro-climate has sparked a number of studies attempting to inform architectural, urbanism and landscape practices (Davies, Steadman and Oreszczyn, 2008; Smith and Levermore, 2008 and Bowler *et al.*, 2010).

4.3.4 Physiological parameters

Physiological parameters refer to the bodily reactions to the climate as well as some possible coping mechanisms and strategies a person puts in place to increase their comfort level. The second major component of thermal comfort is therefore biological. For example, SWR leads to an elevation of the body temperature. Inversely, the absence of SWR can be compensated by the generation of internal heat. Additionally, high humidity may lead to inefficient sweating and cooling, wind may buffer higher temperatures or may dehydrate etc. The theoretical basis to link the microclimate to human physiology is to use thermal indices that rely on heat generation, transfer and dissipation within and at the boundary of the human body (Honjo, 2009). These indices rely on the presumption of homeostatic and dynamic reaction to external conditions, such as shivering when cold and sweating when warm. (Matzarakis and Mayer, 1996). This relation between the body and the environment has notably been described using a formula, the Munich Energy Balance Model for Individuals (Höppe, 1999). This equation uses the four aforementioned climatic variables and describes its interaction with the thermal properties of the human body. In this approach, clothes and the physical activity (sitting, walking or more intense exercising) are considered as important as the former provide some level of insulation (Schiavon and Lee, 2013) and the latter influences the rate of internal heat generation (Matzarakis and Amelung, 2008).

Other physiological factors have been highlighted as playing a role in thermal comfort. While gender seems to play a role in indoor thermal comfort (Petrescu, 2017), very few studies, if at all, report this in outdoors situations. Age, however, possibly mediated by lower heat generation and lower thermal sensitivity, is usually a factor; other may variably include body mass and skin colour (Kruger and Drach, 2017). These factors are all regrouped under “individual characteristics” in the framework (see Figure 4.1).

The last noteworthy physiological parameter is acclimatisation which refers to the process of adjusting oneself to the average prevailing climatic conditions of a place in a yearly, seasonal or short-term fashion (Lin, 2009). Concerning acclimatisation, Krüger *et al.* (2017) demonstrated that very short term, within thirty minutes, adjustment to outdoor conditions occurred. After participants had been placed in comfortable indoor conditions for a length of time, their immediate perception of the outdoor conditions was skewed, however after 30 minutes their prediction of the weather was in line with reality.

Acclimatisation over days or weeks rather than minutes was also highlighted by the fact that warm conditions were considered more comfortable after multiple days of heatwave. Similarly, Nikolopoulou, Baker and Steemers (2001) demonstrated the adaptive capacity of a person over the course of a few weeks. They indeed obtained a good correlation between individual neutral temperatures as a function of mean air temperature for the month prior to the interview. On longer time scales, a few months, acclimatisation is visible in a lot of studies that observe a difference in neutral temperatures according to seasons (Liu, Zhang and Deng, 2016) or across different climate zones (Aljawabra, 2014 for example) which is logical since people adapt to their average climatic conditions. Adaptation was evident in the RUROS study (Nikolopoulou, 2004) which showed that people were comfortable in different climatic conditions and across seasons as a result of a seasonally and geographically adjusted thermal comfort regardless of the actual climatic conditions considered.

4.3.5 Psychological parameters

Indoor and outdoor thermal comfort have been shown time and again to be insufficiently predicted by comfort indices alone. Beyond the capacity for physiological acclimatisation and the actual values of the physical parameters, psychological components have been theorised to act in parallel with the more traditionally researched components (Nikolopoulou and Steemers, 2003). For instance, Fountain, Brager and de Dear (1996) concluded that inter-personal and intra-individual variabilities could not be explained solely by physio-climatic reasons. This concept was extended to outdoor conditions in Nikolopoulou and colleagues' early work (Nikolopoulou, Baker and Steemers, 2001) that noticed the disjoint between a comfort index (the Predicted Mean Vote, PMV) and the reported thermal sensation (Actual Sensation Vote, ASV). Indeed, when microclimate, spatial characteristics and physiological state have all been taken into account then a normally distributed comfort level would be expected; and perhaps such variables as season, age and type activity practiced would predictably influence this distribution (Kántor, Kovács and Takács, 2016; Krüger and Drach, 2017; Petrescu, 2017). However, this is not the case. Thermal sensation reports not matching with the objectively measurable reality have occurred in variable amounts (Nikolopoulou, Baker and Steemers, 2001; Liu, Zhang and Deng, 2016). Similarly, Knez and Thorsson (2008) underlined the disparity in thermal evaluation as a function of culture (Swedish versus

Japanese) and as a function of personal environmental attitude (urban versus open-air). In other words, it was highlighted that psychological factors were acting in conjunction with physical and physiological elements (Nikolopoulou and Lykoudis, 2006).

In the presented framework, some psychological components can be grouped together. Thermal history may be seen as encompassing thermal expectation, preference and long-term experience. These notions describe how past events and prior thermal experiences lead to the creation of schemata. A schemata is described by Lenzholzer (2008) as a set of characteristics assigned to a situation, place or event. These have been shown to shape the behaviour of urban dwellers (Nikolopoulou and Steemers, 2003; Eliasson *et al.*, 2007). It could take the form of seeking places with high radiative load (very sunny) to balance a recent history of being cool (in an air conditioned office) (Katzschner, 2006) for example.

The aesthetic experience regroups aesthetic appreciation, preference as well as naturalness. It is similar to Knez' (2005) theory of the influence of "Place". According to Knez *et al.* (2009), "place" plays an important role in thermal comfort since it encompasses a spatial component, an emotional and intellectual reaction as well as a specific climate. For these authors, the interplay between identity of the self and the projected attributes of the place as well as the attachment to it one may have with it may influence the feeling of thermal comfort. Evidence supporting this relationship has been found. Krüger (2017) found that preference for elements of street environments lead to improved thermal sensation and Klemm *et al.* (2015a) found that landscape preference may bias a person into feeling more comfortable than they should be. In both instances, people's perceptions did not match comfort indices where the factors that varied were the degree of street openness in the former and the kind of vegetation planted in the latter.

Lastly, contextual factors have been shown to play a role in the immediate perception of thermal comfort, irrespective of the actual climatic conditions. These were notably highlighted in Nikolopoulou, Baker and Steemers (2001) and Nikolopoulou and Steemers (2003) and include how variable the weather is (environmental stimulation), if a respondent is alone or accompanied (social context) and the reason to be outdoors (perceived control).

4.4 Aesthetic appreciation and naturalness

It has been made clear that perceptual qualities of the place as well as the current emotional state and prior thermal experience (whether short or long term) all shape the final and overall thermal sensation of comfort; which explains the potentially high, inter and intra-individual, variability (Fountain, Brager and de Dear, 1996; Krüger, 2017). The factors that were considered in this study were chiefly aesthetic appreciation and naturalness; both of which are influenced, but not necessarily, by the presence of greenery.

The aesthetic appreciation refers to Knez *et al.*'s (2009) connection to "place". The authors described it as an emotional and intellectual connection to the space a person is in. The working definition of aesthetic appreciation may be: "the perceptual, including sensory, qualities of a scene or a place which connects intellectually and emotionally with the self in either a conscious or unconscious way". In its relationship with the natural environment, the aesthetic experience has been well described (in Knez and Thorsson, 2008 and Klemm *et al.*, 2015b). Marselle *et al.* (2014) attempted to connect descriptors of the aesthetic experience of nature with psychological benefits. They notably found that contact, i.e. close proximity, with Nature created a lasting positive effect in participants. Within the Attention Restoration Theory, it may also be said that Aesthetic experience is the mediator through which natural landscapes rest fatigued intellectual cognitive processes (Grahn and Stigsdotter, 2010).

Naturalness is a concept that describes where a place lies in the "natural to artificial" spectrum. The latter covers a wide array of situation, from pristine, untouched (by humans) "nature" to fully built-up hard environment. Naturalness refers to both a physical reality that can be described and to a perception that may be recorded but both pose issues. Özgüner and Kendle (2006) proved that people could definitely discriminate between levels of naturalness. For instance, they recorded different degrees of appreciation whether an environment was considered as naturalistic or formal and natural or urban. Describing naturalness may be done, as in Ode *et al.* (2009), by distinguishing between levels of designed landscape, from coherent to chaotic for example. Decomposing naturalness in terms of its parts, or its elementary components, has proven a challenge. From a theoretical standpoint, Ode, Hagerhall and Sang (2010) argued that three sub-elements came together in the concept of naturalness. These sub-elements were the level of disturbance, of coherence and of visible human care. These individual sub-elements are still challenging to pull apart when attempting to study psychological reaction to naturalness. Common measures of naturalness involve giving landscape scenery a numerical value of a disorganisation index (entropy) or quantify the amount of edges present (Kardan *et al.*, 2015) which are properties of Nature if left to her own device, without human intervention. Hence, naturalness has components humans may innately be able to recognise but a reliable, quantifiable, description of it is not yet available. Additionally, the interpretation of it seems to be dependent on other personal and cultural modifiers (van den Berg, Vlek and Coeterier, 1998). For example, Knez and Thorsson (2008) observed significantly different perception of similar park designs across two distant cultures (Swedish and Japanese). They explained that culture, as an information system shared by members of a specific group, codes for the interaction with the physical world. Such information system being group specific are thus expected to differ between groups and are likely to lead to different interactions and perceptions of the physical world.

Beyond what constitutes the judgement of naturalness, it potentially plays a moderating role in outdoor thermal comfort by increasing the tolerance to discomfort one feels for a given physical environment and physiological state (Nikolopoulou and Lykoudis, 2006). This may be understood, for instance, as the expectation that a natural environment may be more prone to variations or a certain biotope is naturally more wet or dry, exposed or sheltered etc. It represents a blend of the assimilation of certain qualities of the place with the expectation of comfort derived from such a place. Even though the link between outdoor thermal comfort and naturalness may seem logical, data backing it up is scarce. The limited literature on the topic includes the study by Rajapaksha and Rathnayaka (2014). In their study, they report Sri Lankan’s park users to be thermally comfortable beyond what would be considered so in humid tropical conditions by thermally adapted people. The authors further suggested that the naturalness of the setting, with a choice of niche locations (close or far from the water, exposed or shaded from the sun) gave greater perceived control to users and thus increased the acceptability of the outdoor conditions. In a similar fashion, Hirashima, Assis and Nikolopoulou (2016) report a greater degree of tolerance for equivalent thermal conditions in a square with a higher degree of naturalness (that included green areas and water features) than one next to busy roads.

To date, only a single study considered naturalness explicitly at the onset of a thermal comfort study (Shooshtarian and Ridley, 2017). They reported that naturalness did not correlate with thermal comfort. This is an unsurprising conclusion granted the flawed methodology they employed. Neither did they define naturalness nor give any quantification of how natural their study sites were. It seems their study sites included sparse mature trees in individual concrete planters or a row of young trees interspaced by bushes within a highly built up environment. This type of highly manicured and contained greened area may be considered as having low degrees of naturalness with high amount of straight edges and high degree of organisation (Kardan *et al.*, 2015). The only item of their questionnaire explicitly related to naturalness was a closed question asking respondents if they agreed with the establishment of new green spaces. The other question referring to naturalness was the "key feature of the place" which included answers with vegetation. "Better ambient conditions" was, however, the most chosen answer (and not any item related to the "natural features"). This reinforces that respondents, too, did not view the space as natural. Given their "naturalness" question was related neither to the degree of naturalness of the space nor to its perception, it is therefore unsurprising that they found no correlation between thermal comfort and naturalness. Hence, putting aside this precise study but using the aforementioned observational inferences, to date, the literature suggests that indeed naturalness acts upon thermal comfort in widening respondent's tolerance threshold.

4.5 Choosing a thermal comfort index

The assessment of outdoor thermal comfort is rendered more complicated by the variable and unpredictable nature of climatic parameters (Nikolopoulou and Lykoudis, 2006) yet it bears formidable importance with regards to the range of activities that can be undertaken and the general quality of life of urban dwellers (Chen and Ng, 2012). Many indices have been proposed throughout the last decades (Honjo, 2009) to provide relevant information on how humans perceive their thermal environment and whether it was acceptable or not. Indices provide measures of human comfort or health (Matzarakis and Mayer, 1996) but, as argued by Eliasson *et al.* (2007), may also provide a chance for designers to quantify or predict the impact of their development work.

This study uses the Physiological Equivalent Temperature (abbreviated PET henceforth). Initially proposed by Höppe, its usefulness has been proven by the work of Matzarakis and colleagues (in Lin and Matzarakis, 2008 and Matzarakis and Amelung, 2008 for example) and made easier to use through the development of the RayMan software (Matzarakis, Rutz and Mayer, 2010). The PET is based on a human energy balance which includes energy generation, transfer and loss through different mechanisms (such as Work or Perspiration). In turn, this heat balance is influenced by four climatic variables: air temperature, wind velocity, vapour pressure and mean radiant temperature (Höppe, 1999). This index incorporates both physiologically and physically (climatic) relevant parameters. The PET's output is the air temperature, under standard indoor conditions, that would be necessary to attain the same physiological state that a person is in when exposed to outdoor conditions. Essentially, the PET reduces a complex outdoor situation (comprising the wind, solar irradiation, etc.) into the temperature that a human would feel in an indoor situation (Höppe, 1999; Matzarakis & Amelung, 2008).

The PET is more useful than using just the outdoor air temperature or the mean radiant temperature (Honjo, 2009). Although some studies have reported good correlation between comfort rating and air temperature, the PET has the benefit of taking into account all possible interactions between the atmosphere and the person. Its calculation incorporates the level of clothing which confers a resistance to heat transfer (Matzarakis and Mayer, 1996). The PET also exhibits more flexibility. Indeed, the same PET value may be obtained under different conditions that metabolically provide the same level of comfort. For example, a higher wind speed can compensate for higher solar radiation. The PET's last advantage is its expression in degrees Celsius which permits cross-comparisons of the thermal comfort and preference over a broad range of climatic and geographic background as is the case between Hirashima, Assis and Nikolopoulou's (2016) study in Brazil and Lin's (2009) in Taiwan.

4.6 Objectives

This study focuses on the perception of comfort and its moderation by perceptual factors. It does so by seeking conjointly reported thermal sensations and microclimatic conditions in order to derive a thermal comfort index. As highlighted earlier, previous research projects have established that thermal sensations can be mediated by some perceptual, psychological elements. Relating back to the delivery of ecosystem services of urban meadow vegetation, it is unknown whether its presence may alter in any significant way thermal sensations. Indeed, meadow vegetation as an instance of nature could potentially alter the perception of the environment in a way that increases or decreases thermal comfort. Hence, drawing upon the results of the appreciation of the Grey to Green and subsequent improvement of the perceptual qualities of the streetscape (Chapter 3) and adding thermal comfort questions as well as microclimatic measurements this chapter will have the following objectives:

- Calculate a local neutral temperature range
- Find evidence of the influence of physiological factors on thermal comfort
- Find evidence that perceptual elements of the naturalistic meadow vegetation moderate thermal sensation or interact with the feeling of comfort

4.7 Questionnaire and survey design

The study site was the Grey to Green as described in Chapter 2. The survey (see Appendix 1) used in the previous chapter on perception also contained questions that regarded specifically thermal comfort. This part of the questionnaire was based on previous work by Nikolopoulou (2004). Respondents were asked how warm they felt at the moment; this is termed the Actual Sensation Vote (ASV) and was scored on a 5-points scale. The available responses ranged from “Very cold” to “Very hot”. Afterwards, the respondents were asked how they felt about the wind. They had to choose from a 5 points scale ranging from “No wind” to “Too much wind”. Then respondents were asked about the humidity. The latter was 3-point scale responses with the following possible answers: “Damp”, “OK” and “Dry”. Finally, with a closed question, respondents were asked if they felt thermally comfortable or not. Asking respondents both about their thermal assessment (ASV) and a more global comfort was rendered necessary by the fact that Nikolopoulou & Steemers (2003) highlighted that people might feel comfortable even in cases of slight objective discomfort. Gender, age and reason to be on the site were also recorded. The interviewers also noted whether the respondent was walking/performing a task or was sitting down. The latter observation is crucial in future use for PET derivation as activity level (energy expenditure) may be better estimated. Similarly to the Chapter 3 procedure, a representative sample of 322 to 341 people was sought. Three time periods were sampled: 8:00 to 11:59 (morning); 12:00 to 14:59 (mid-day); 15:00 to 19:00 (afternoon). The lead author and two interviewers participated in the street survey with a defined text to introduce the survey, the location of the interviews within the scheme is indicated in Figure 4.2. Like previously, this survey had received ethical approval.

In addition to the street questionnaires, weather data was also collected during the survey period at a rooftop situated about 800 metres away from the study site. Air temperature, solar radiation, wind speed and humidity were all recorded at this station as suggested by Johansson *et al.* (2014).

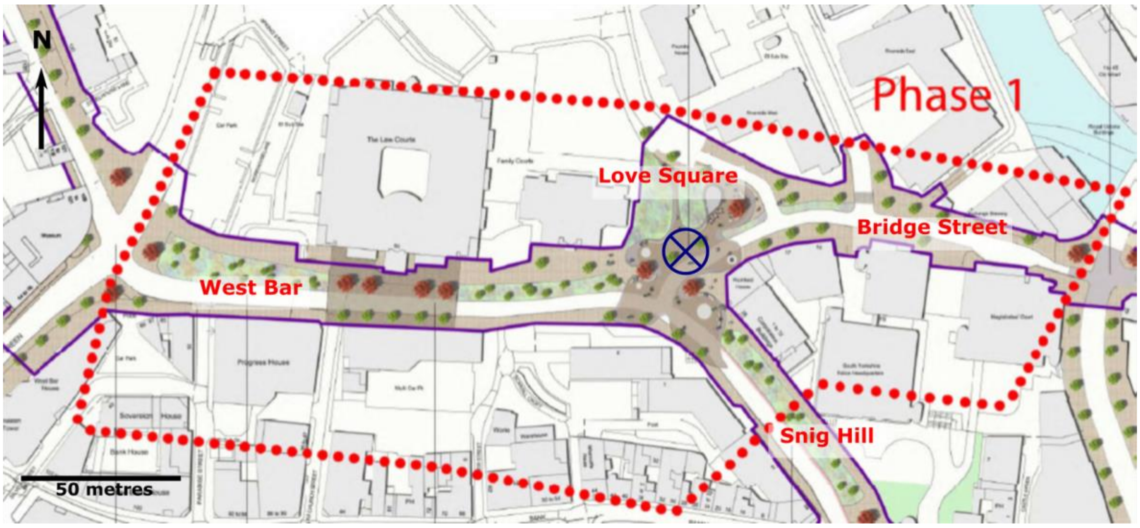


Figure 4.2: Map of the Grey to Green with street names. The circle with the cross indicate the area where the interviews took place during the summer of 2016. These areas are concrete footpath with a sky view factor of 1 but are still in sight of the planted areas.

4.8 Results and discussion

4.8.1 Sample and weather description

Similarly to the previous chapter on perception, 339 questionnaires were obtained over a period of ten days during the months of July and August 2016. The sample comprised nearly as many men as women and the most represented age groups were the 26 to 35 years old (n = 105) and the 36 to 45 years old (n= 86) (see Table 4.1 for further details).

Table 4.1: Characteristics of the sample (n = 339.).

Sex		Age groups		Time period		Reason to be on site	
Male	169	18 - 25	74	Morning	88	For work	183
Female	170	26 - 35	105	Mid-day	144	For leisure	70
		36 – 45	86	Afternoon	107	On an errand	52
		46 – 55	51			To visit the site	34
		56+	23	Week-day	241		
				Week-end	98		
Activity level		Walking/being active	237			Sitting	102

During the survey campaign, the mean air temperature was 19.0°C in the morning, 20.2°C during mid-day and 18.0°C in the afternoon (summarised in Table 4.2). Overall, air temperatures between 18 and 20.5°C were most frequent. The mean relative humidity was 65.8% in the morning, 63% at mid-day and 64.4% in the afternoon. Mean wind speed, at 1.1 metres, was 1.8 $m.s^{-1}$ in the morning, 2.5 $m.s^{-1}$ during mid-day and 3.1 $m.s^{-1}$ in the afternoon. Solar radiation was generally low with a mean of 551.8 $W.m^{-2}$ at mid-day and 500.6 $W.m^{-2}$ overall.

Table 4.2: Average microclimatic conditions per period of the day plus or minus the standard deviation

	Morning 8:00-11:59	Mid-day 12:00-14:59	Afternoon 15:00-19:00	Overall
Air temperature (°C)	19.0 ± 2.4	20.2 ± 1.1	18 ± 1.5	19.2 ± 1.9
Relative Humidity (%)	65.8 ±3.3	63 ± 5.9	64.4 ± 6.5	64.2 ± 5.7
Wind speed at 1.1m ($m.s^{-1}$)	1.8 ± 0.4	2.5 ± 0.6	3.1 ± 1.1	2.5 ± 0.9
Solar radiation ($W.m^{-2}$)	415.6 ± 220.6	551.8 ± 201.7	502.4 ± 198.9	500.6 ± 213.1

Due to equipment unavailability, no on-site measurements could be obtained. The following comfort index calculations were therefore limited to the data acquired from a rooftop weather station situated less than a kilometre away from the site itself. This constitutes a limitation of the present research results as differences in elevation of the equipment and built context would notably influence wind patterns. Clouds might also not cover equally both zones despite them being close, leading to disparities in amount of solar radiation received. This data presented as part of this study could still be considered representative as a later comparison of air temperatures taken next to the Grey to Green and at this weather station indicated no significant differences between both (Figure 6.5 in Chapter 6). As such both locations could be considered as having relatively close micro-climatic conditions. It remains this climatic data is a substitute, but the closest available to the site's true conditions.

4.8.2 Immediate perception of comfort

Respondents almost unanimously responded that they felt comfortable (99.1% of the sample). A similar situation was found by Nikolopoulou and Lykoudis (2006) with a proportion of around 85% for Sheffield in summer. Neither of the three climatic perceptions were neutral. The average votes (noted $\bar{x}$) for the temperature perception (Actual Sensation Vote, ASV) and the humidity perception were positive though close to zero ($\bar{x} = 0.45$ and $\bar{x} = 0.14$ respectively). Wind perception was not neutral either but its average score was negative ($\bar{x} = -0.21$). Thus, on average, respondents indicated they felt closer to “Neither cool nor warm” (neutral thermal comfort), that the humidity was close to “OK” and that wind was close to “OK” with a slight directional bias in each case.

The responses were tested against the null hypothesis that if respondents felt comfortable in all three dimensions then their respective median response would be centred on 0. For this, a One-Sample Wilcoxon Signed Rank test was used. Results indicated that the median of the scores was significantly different from zero ($p < 0.05$) (data not shown), hence none of these perceptions is indicative of true neutral perceptions. For the ASV particularly, these results are in line with previous research findings in Europe where respondents lean towards answering feeling “warm” in summer conditions (Nikolopoulou, Baker and Steemers, 2001), as visible in Figure 4.3.

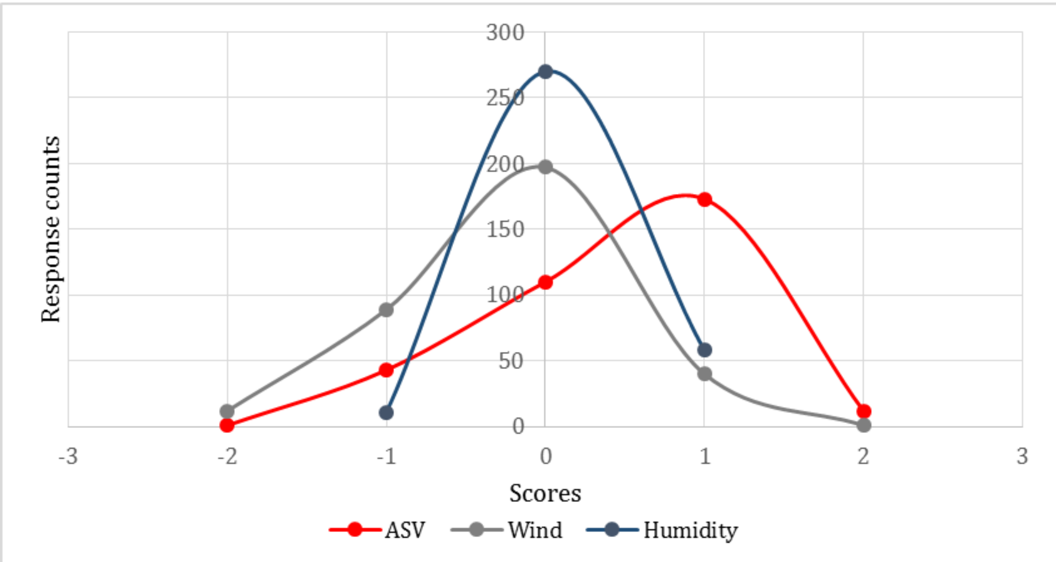


Figure 4.3: Distribution of responses to the subjective assessment of air temperature (ASV), wind and humidity. Unlike the two others, humidity is quantified on 3 point scales items. Distributions were centred on 0 to designate neutral comfort.

A variety of factors that may interact with thermal comfort were included in the questionnaire and were tested for, namely gender, time of the week, time of the day, the level of activity (walking or doing a task or sitting/standing still), perceived choice (reason to be there). Perceived control of the situation, as argued by Nikolopoulou and Steemers (2003), can affect the sensation of comfort one may feel. As such, the sample was divided according to the reason to be on site. On the one hand, those who responded being present for work or on an errand were considered to have no choice for their presence (coded "0"). On the other hand, those who responded being here for leisure or to visit the site specifically are considered to have had a choice to come to the site and therefore having perceived control (coded "1"). The potential interaction between aforementioned factors and responses were probed using a Mann-Whitney test. Lastly, possible interactions between age groups and scores were tested using Spearman's Rank-Order Correlation. The number of respondents reporting feeling uncomfortable was too low to perform the corresponding in-between groups' analysis.

The Mann-Whitney tests (reported in Table 4.3) returned no significant interactions between gender, activity level and perceived choices on responses. The test, however, showed a significant difference between responses depending on the period of the week (weekday versus weekend). The difference in ASV and humidity assessments may, however, be explained by significant differences found, using a T-test, in air temperature and relative humidity between week days and weekends (both with $p < 0.05$). No significant differences were found between the scores of different age groups using Spearman Rank Order correlation tests; although in the ASV's case it was close to significance ($p = 0.063$). Differences in wind and humidity perception were noted when the sample was divided between weekends and week days. To test for an effect of the physical parameters themselves on the perception votes, an ANOVA was conducted. Results of this test showed significant differences in wind and humidity measurements between these two periods of the week. This suggests that differences in the perception of the wind and humidity between weekdays and weekends due to actual climatic differences.

Table 4.3: Results of Mann-Whitney tests to assess potential score differences between binary categories. Reported rho value are the results of a Spearman Correlation to assess potential interactions between responses and multi-levelled categories. Statistics were done on n = 339. Asterisks denote significance for α = 0.05.						
Items	Gender U (p-value)	Perceived choice U (p value)	Activity level U (p value)	Age Rho (p value)	Period of the week U (p value)	Time of the day Rho (p value)
Actual Sensation Vote	14346.5 (0.982)	11745.5 (0.532)	11731.5 (0.771)	0.101 (0.063)	9887.5 (0.010)*	-0.088 (0.107)
Wind perception	13491.5 (0.274)	11337.0 (0.231)	11253.5 (0.339)	-0.089 (0.103)	11572.5 (0.744)	0.299 (<0.05)*
Humidity perception	14166 (0.753)	11969.5 (0.667)	11746.0 (0.723)	0.035 (0.516)	10584.0 (0.032)*	-0.119 (0.028)*

4.8.3 PET calculation

The RayMan software was used to calculate the PET (Matzarakis, 2012). An upwards fish-eye photograph of the site was used to determine the Sky View Factor. The site being in a part of the city with low buildings and wide streets, the SVF was equal to 1. Effectively, the site could be considered an open urban area in which incoming solar radiation encounter minimal or no obstacles. Firstly, meteorological variables must be inputted in the program. The temperature, wind and humidity data points were based on 30 minutes average measurements. Solar irradiation data was taken on the average of the ten minutes preceding the questionnaire time stamp (as the latter was noted at the end of the interview) and the value at the time stamp. This choice was guided by the fact that the change of radiation level (by cloud cover notably) is known to strongly affect the mean radiant temperature (Matzarakis, Rutz and Mayer, 2010) and data immediately before and within the time window of the interview was deemed more representative than longer time averages.

The measured wind speed had to be adjusted to 1.1 metres, the human centre of gravity. Equation 1 is the Wind Profile Power Law previously used by Gulyás, Unger and Matzarakis (2006).

Equation 1: $V \approx Vref \times (\frac{h}{href})^{\propto}$ where $\propto = 0.12 \times Z_0 + 0.18$

V is the calculated wind speed, V_{ref} the measured wind speed, h and h_{ref} their respective heights. The exponent α is usually empirically derived but may be estimated using Z_0, the surface roughness of the site. Calculations were made using for $Z_0 = 0.4$ due to the fact that the site is fairly open yet remains within a city environment.

Then, information about the person is input. To simplify calculations, the PET was derived for a ‘standard 30 years old male’ (Krüger, Minella and Matzarakis, 2014). However, the following assumptions were used: respondents present for work were given a standard clothing value of 0.9 clo (Höppe, 1999) and those present for different reasons were given a value of 0.6 clo, based on Schiavon and Lee’s conclusions for summer clothing (2013). Additionally, those walking were assumed to have an activity level of 2.3 MET (133.9 $W.m^{-2}$) corresponding to a fast pace and those sitting were assumed to have an activity level of 1 MET (58.2 $W.m^{-2}$). Each respondent to the questionnaire was then assigned an adjusted PET value based on its activity and reason to be on site.

During the survey campaign, the average PET was 19.7°C while the median PET was 18.5°C. Following the method presented in de Dear and Brager (1998) and used by such authors as Lin and Matzarakis (2008), PET bins were made for each 1°C intervals of the adjusted PET. As shown in Figure 4.4, the most frequent PET encountered over the survey period was 16.5°C which occurred 49 times. It is followed by 17.5°C which occurred 33 times. Both 14.5 and 21.5 °C bins occurred 27 times.

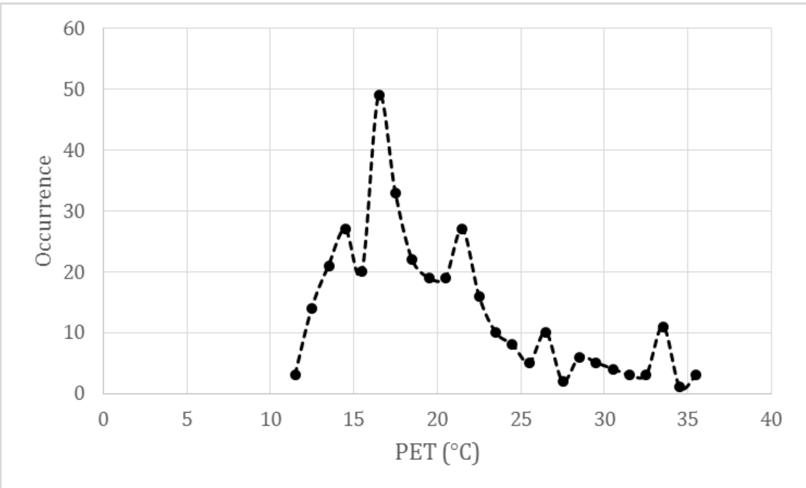


Figure 4.4: Distribution of the occurrence of 1°C PET bins over the course of the study.

4.8.4 Neutral temperature calculation: Regression method

Next the Neutral Temperature, or the neutral PET in this study, can be calculated. It corresponds to the temperature for which the mean ASV is equal to 0. This was achieved by plotting the mean ASV per PET bins of 1°C against the PET, as shown in Figure 4.5. Regression analysis was performed and Equation 2 was obtained.

Equation 2: $Mean\ ASV = 0.048 \times PET - 0.487\ (R^2 = 0.610, \text{p} < 0.01)$

Using Equation 2, the neutral temperature or neutral PET may be obtained. For mean ASV of 0, T_n = 10.15°C. In other words, in a virtual indoor scenario with standard conditions, the equivalent air temperature to obtain the same level of comfortable heat balance would have to be of 10.15°C. As explained by Aljawabra (2014), the PET bins may be widened in order to improve the R^2 value. In this study, a PET bin of 2°C indeed increases the R^2 to 0.8437 and gives a T_n of 10.43°C. Additionally, a PET bin of 3°C gives a R^2 of 0.8857 and a T_n of 9.83°C (Data not shown). Through bin widening, the R^2 value has indeed been increased and still renders a value of around 10°C.

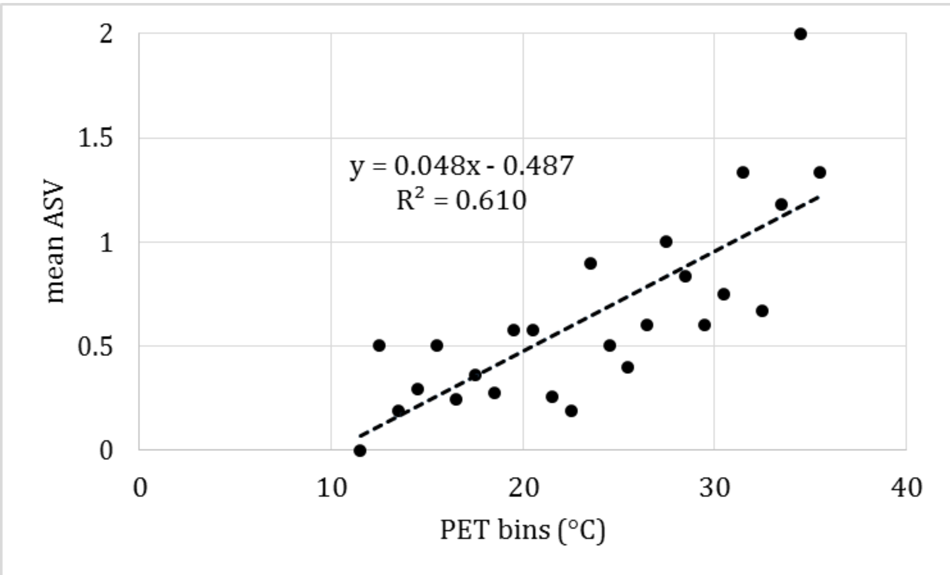


Figure 4.5: Mean ASV per 1°C PET bin. The linear regression equation gives a T_n of 10.15°C for mean ASV = 0.

This method was used in a similar fashion by Liu, Zhang and Deng (2016) in China on aggregated data over one hour on a very large sample (7851 respondents). It is worth noting that in this study the PET explained 61% of the variation observed in the

ASV. This is very similar to the aforementioned study which found that the PET explained between 52 to 79% of the Thermal Sensation Vote (TSV, similar to the ASV but on 7-points Likert scale). This validates this study's methodology on two aspects. The first is that the sample size was sufficiently large to replicate a similar pattern than a study with much higher number of respondents. Secondly, there seems to be no major statistical differences whether the ASV or the TSV are employed. Nikolopoulou and Steemers (2003) reported that, in their work 50% of the variations could not be explained by microclimatic factors. The aforementioned results, supported Liu, Zhang and Deng's (2016) conclusions, indicate that climatic factors account for more than previously thought. This increase of 10% may stem from the use of a different thermal comfort index. Indeed, as discussed earlier, the PET includes thermoregulatory processes as well as clothing and activity levels. The increase in complexity of the comfort index is equating to an increase in the prediction power of comfort from microclimate variables as demonstrated by the increase of the coefficient of determination. While these results are encouraging, it still remains that about 40% of the variations of ASV are unexplained by microclimatic factors.

4.8.5 Neutral Temperature: Probit model method

The Probit model may be used when the researcher wants to predict the temperature (PET in this study) at which more than 50% of respondents will vote for a warm ASV instead of the neutral one (Nikolopoulou and Lykoudis, 2006; Aljawabra, 2014). Multiple forms of this technique have been reviewed by Kántor, Kovács and Takács (2016) and they found that all straight applications of the probit models render neutral temperatures that were similar. Based on their large Hungarian sample size of 5800 respondents, they determined that the three commonly used probit models differed by a maximum of 0.2°C. They offered an alternative technique which was to consider the maximum distribution peak of the TSV = 0 as the true neutral PET. However, as they noted, their technique did not provide a good fit for TSV < 0 in summer. On this basis, their technique was discarded.

The chosen method was the random allocation of 50% of neutral votes. This may be done by, firstly, defining a binary variable with two values "cooler or neutral" and "neutral or warmer" with values equal to the sum of the probabilities of "very cold" +

“cool” + “neutral”/2 and “neutral”/2 + “warm” + “hot” respectively. The probability of occurrence of each ASV category was calculated for each PET bin and then summed to create the values of the aforementioned binary variable. These values may then be used against a standard Probit Value chart to obtain the Probit value for each PET bin. Regression analysis may then be used using the $\log_{10}$(PET) against the probit values. The $\log_{10}$(PET neutral) can be obtained by using the regression equation thus obtained for y = 5 (probit value corresponding to a 50% occurrence or chance) (Data not shown). The temperature above which more than 50% of respondents will cast positive ASV votes, i.e. the neutral temperature, may now be calculated. Using PET bins of 3°C, which provided the highest R^2 value for the regression analysis, the neutral temperature was 10.9°C (R^2 = 0.8584).

4.8.6 Issues with standard neutral temperature derivation methods

The two previous methods certainly yielded comparable results, yet neither are compatible with observations. Indeed, these results indicated neutral temperatures of around 10°C which, according to the distribution of the occurrence of 1°C PET bins (Figure 4.4), never occurred during the sampling period. It is worth mentioning that although it was summer, the temperatures (as expressed by the PET) were on the lower end of the expected comfort zone (see Figure 4.6 below), leading to a possible asymmetry between expected results for summer conditions and the observations. However, despite these observations the vast majority of the sample reported feeling comfortable overall and the majority of respondents felt either “neutral” or “warm” (as shown in Figure 4.3).

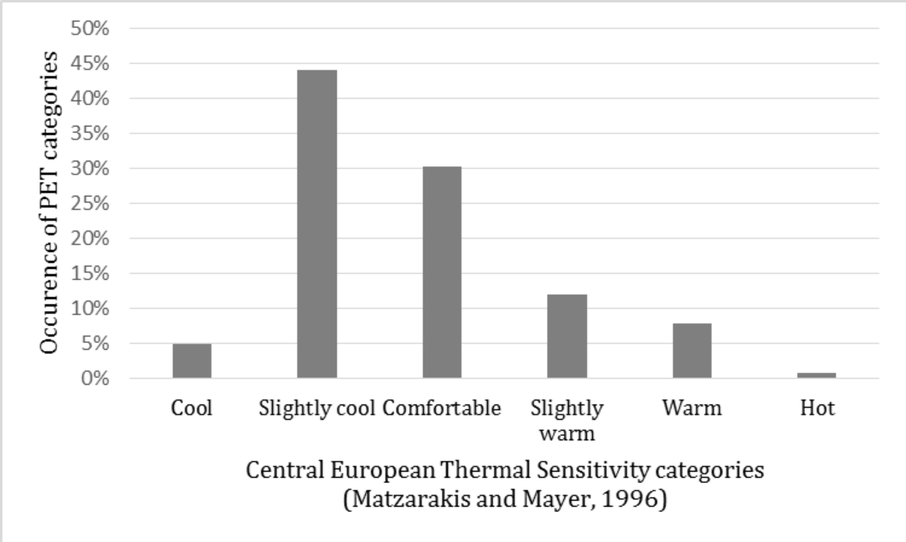


Figure 4.6: Distribution of the Central European PET sensitivity categories. According to this classification about 50% of the respondents were questioned in colder conditions yet respondents indicated at 51% feeling warm.

There is thus a divide between the neutral temperature prediction via the two methods used and observed PET values. This discrepancy may be explained by the data sets having non-normal distributions. From a formal statistical point of view, a Shapiro-Wilk ($p < 0.05$) and a Levene's test ($p < 0.05$) indicated that the sample violated both the assumption of normal distribution and homogeneity of the variance. As both methods are general linear models, they require both of these assumptions to be met to produce coherent results. Figure 4.7 further shows that both the "warm" and "neutral" categories do overlap consistently, explaining the difficulty to find a mean ASV per PET bins. Additionally, unlike other studies, a near total level of comfort with the thermal environment was reported meaning that the data must be handled through alternatives to the standard adaptive methods (Humphreys, Nicol and Roaf, 2016).

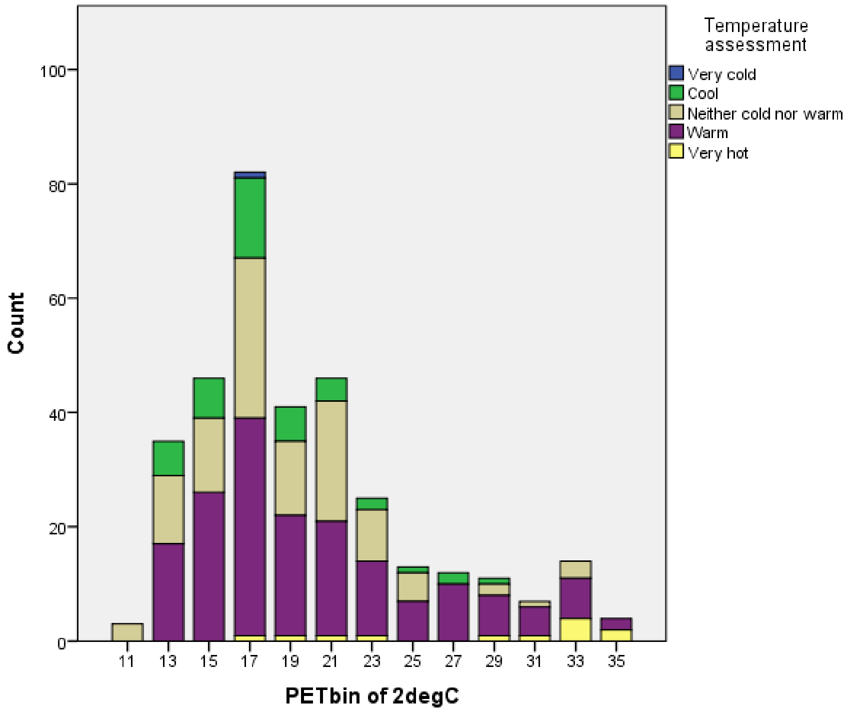


Figure 4.7: Distribution of ASV categories per 2°C PET bin. No clear trend of ASV categories may be seen as their respective distribution is non-normal and significantly overlap.

4.8.7 Neutral comfort range: ATSI method

A similar issue was encountered by Gómez-Azpeitia *et al.* (2012) under very hot climates in Mexico, whereby respondents reported feeling comfortable in temperatures above 30°C (using a globe thermometer) and the results of their linear regression were aberrant. In their work, they reported that conventional methods, such as the ones based on straight linear regression, may not yield applicable results in the case of non-normally distributed weather conditions. They hence proposed a different method to derive the neutral temperature (Gomez-Azpeitia *et al.*, 2011) called the Averages of Thermal Sensation Interval (ATSI). Broadly speaking, instead of using the mean ASV vote per PET bin, the authors used the mean PET per ASV category. They then forced normality of distribution in the data by considering each individual ASV category as an independent data set with a mean PET with its own standard deviation. Regression analysis was then applied independently to these five new sets (if available): mean temperatures (Tm), means ± 1 standard deviation, means ± 2 x standard deviation. The intercepts of these regression lines with y = 0, equivalent to ASV = 0, represent the neutral temperature. The intersection between ±1 standard deviations and y = 0 then gives the comfort range (see Figure 4.8).

The method was applied to the present data set with the exclusion of the "very cold" category which had only one vote. The neutral PET was 18.9°C (R^2 = 0.77) with a comfort range within one standard deviation of 14.4°C (R^2 = 0.65) to 23.3°C (R^2 = 0.81). The intercept between the +2 standard deviations regression line and ASV = 0 was at 27.7°C (R^2 = 0.83). Inversely, the intercept between the -2 standard deviations regression line and ASV = 0 was 9.4°C (R^2 = 0.35). From this analysis, a credible neutral temperature and comfort range may be derived.

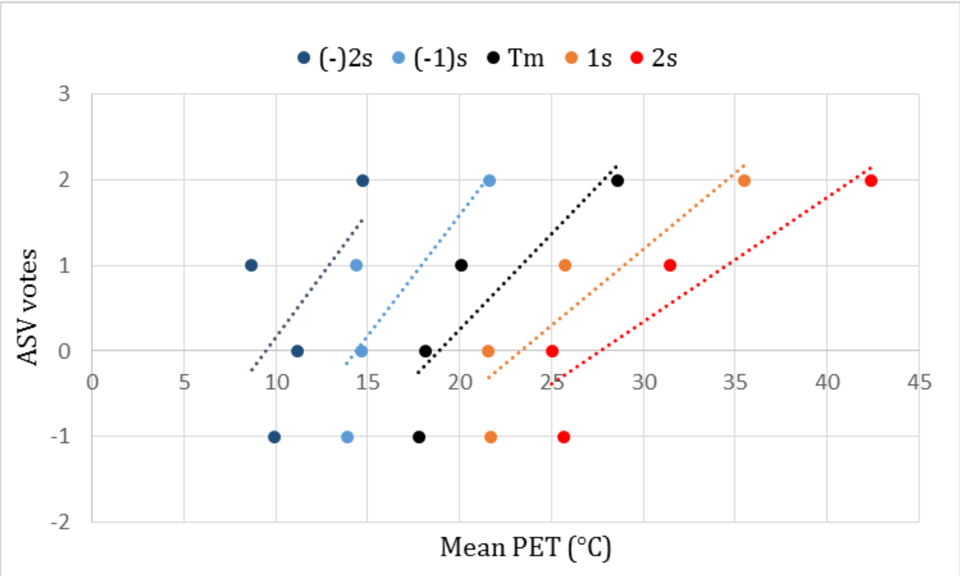


Figure 4.8: Results from the ATSI method using each of the ASV's categories mean temperatures (Tm) and ± 1 or 2 standard deviations. The lines represent each individual linear regression made on these new data sets. The intercept of these lines with y = 0 (or ASV = 0) gives a credible comfort range with values as follow: -2s = 9.4°C; -1s = 14.4°C; Tn = 18.9°C; 1s = 23.3°C; 2s = 27.7°C.

4.8.8 Defining a comfort range for Sheffield

Based on the above results, a new comfort scale for Sheffield is proposed in Table 4.4. Compared to the Central European scale (Lin and Matzarakis, 2008), the neutral sensitivity of Sheffield's inhabitants category is wider (about 9°C instead of 5°C). This may be explained by the wide range of experienced PET throughout the survey campaign, from about PET of 11°C to 35°C (Figure 4.4), and high levels of reported comfort despite such variations. It is therefore credible that Sheffield inhabitants exhibited a larger neutral comfort range. Based on the ±2 standard deviations values, the “Slightly Cool” category was defined to be between 9.4°C and 13.4°C, which is lower than the Central European PET values. The “Slightly Warm” values are aligned, though lower in their upper limit, with the Central European equivalent. Sheffield’s weather being a temperate oceanic climate (Cfb, Köppen-Geiger classification), its summer temperatures do not rise as high as other places on the European mainland and as such its inhabitants may not be as adapted to warmer weather. Overall, these results suggest long-term climatic acclimatisation, whereby inhabitants align their perception to the average local conditions. In Sheffield, the latter take the form of cool summers, below that of the Central European expectation, as well as high PET variability in summer. With this new classification, 71% of the 339 respondents have been interrogated in neutral conditions (distribution in Figure 4.4). This new classification derived using the ATSI method produces a range that is close to the standard 80% acceptability criteria used in indoor conditions (de Dear and Brager, 1998) and outdoor studies (Lin, 2009).

Table 4.4: Proposed equivalence for thermal sensitivity categories based on PET (°C) values between Matzarakis and Mayer (1996) and this study’s results for Sheffield.

Thermal sensivity		Cool		Slightly Cool		Neutral		Slightly Warm		Warm	
Central European	8		13		18		23		29		35
Sheffield	--		9.4		14.4		23.3		27.7		--

4.8.9 Evidence for acclimatisation

The climatic variables for the month prior to the survey campaign were acquired for the hours of 10:00, 14:00 and 17:00 which correspond to the middle timestamps of the three surveyed periods of the day. The wind speed was adjusted in a similar fashion using Equation 1. The clearness index, the ratio of the measured solar radiation over the theoretical maximal radiation for a particular place and time (Eliasson *et al.*, 2007), was also calculated to represent sky conditions. On average during this month, the clearness index was 0.48, the air temperature was 17.0°C, the relative humidity was 69.9% and wind speed was 1.1 m.s^{-1}. As such, on average, conditions were rather uncomfortable for a summer month with high humidity and cloud cover. Median conditions give similar results except for the clearness index which drops to 0.4 indicating a higher amount of unclear days.

With these variables, the PET for each time stamps could be calculated and is plotted in Figure 4.9. During this month, the average PET was 17.3°C (σ = 6.3). The minimum was 6.6°C and the maximum 38°C. Lastly, the average of the daily PET amplitude ($\Delta T = PET_{max} - PET_{min}$) was 7.3°C (with σ = 4.1). As Figure 4.9 suggests, the amplitude of PET that Sheffielders had to live through in the month prior to the investigation was large both between days and within days. Noteworthy, the monthly PET average ± the standard deviation gives a PET interval that is close to the boundary values of the newly defined neutral zone. The slightly higher PET observed during the campaign (average of 19.7°C) compared to the month prior may explain the directional bias of thermal perception towards “warm”. The wide range of tolerated PET during the survey period may now also be understood in the light of acclimatisation, a process by which the body adjusts to environmental cues or changes. As the monthly data shows, the amplitude of PET variation is non-negligible and acclimatisation to this situation could well have led to the pattern of ASV votes observed, which stated “neutral” or “warm” perception over a wide range of PET.

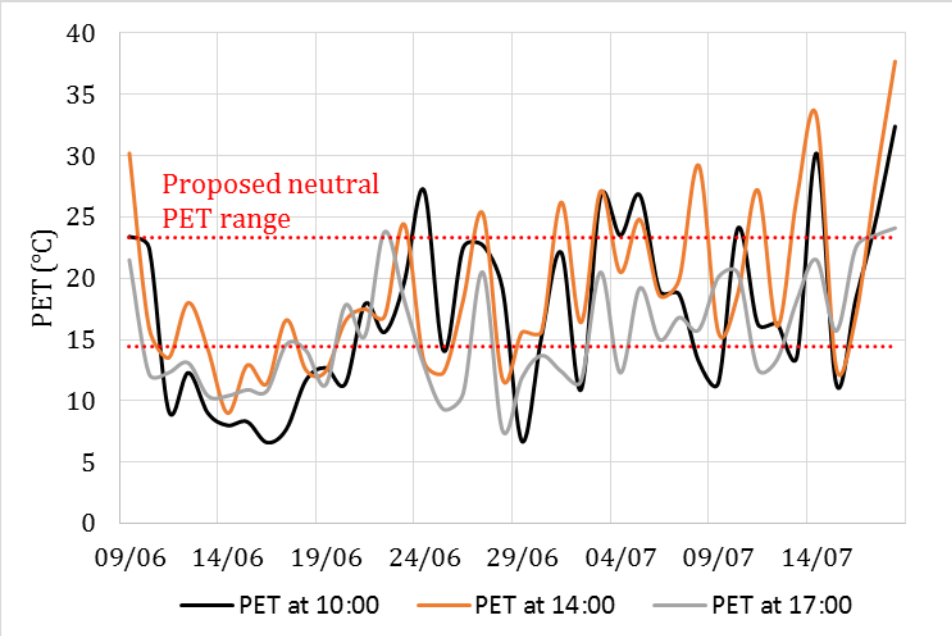


Figure 4.9: PET at three time stamps for the month prior to the survey campaign, the proposed neutral PET range is highlighted.

4.8.10 The psychological influence of greenery

This study was conducted in an urban setting characterised by low building heights and wide streets, an open urban environment in other words, leaving respondents quite vulnerable to weather conditions. An additional consideration to take into account is the potential effect of the Grey to Green on local climatic variables. Green Infrastructure, even at a small scale may positively affect temperatures. For example, Shashua-Bar and Hoffman (2000) showed the effect of trees on lowering the surrounding air temperature. However, Smith *et al.* (2011) demonstrated that in settings similar to that of the Grey to Green, Informal Open Space and Formal Recreation which are land uses more likely to contain grasses and forbs, and within the nearby city of Manchester, air and surface temperature did not significantly depart from the nearby averages. Equally, Armson, Stringer and Ennos (2012) made a strong case on how globe thermometers, from which mean radiant temperature may be calculated and PET derived, was affected by tree shading but not by surface type (concrete or grass) in exposed conditions. Hence, the meadow-dominated vegetation, particularly given it was in its first year of growth (i.e. patchy and lower growing), was not expected to act any different to other grassed areas. As such, it is unlikely that the scheme itself had a major contribution in improving the PET during hot days; even more so as passersby were interviewed on a wide concrete footpath and not in the immediate vicinity of the vegetation. The lack of trees shading the area from incoming radiation did not decrease thermal stress for pedestrian. As such the influence of the vegetation on the PET is considered negligible in this study.

Equally, the wider neutral range of Sheffielders' over that of Central Europeans', derived using the ATSI method, does not fully account for the reported comfort. While 71% of respondents were expected to be in neutral conditions, 99.1% of passersby had claimed to feel "comfortable". Additionally, the linear regression indicated that only 61% of the ASV's variation could be predicted by the PET, in line with Liu, Zhang and Deng (2016). These results highlight that yet other processes are interacting between the sensory reality and its perception and only a portion of subjective assessments are explained by the objective evaluation of thermal comfort (Nikolopoulou and Steemers, 2003). In this instance, Klemm *et al.*'s work (2015b) suggests an interaction between aesthetic evaluation or preference of greenery and feeling of comfort. While respondents in this study rated streets with trees and front gardens more comfortable than streets with trees only, the measured mean radiant temperature predicted otherwise. Therefore, it can be safely assumed that non-objective, i.e. perceptual factors were moderating the thermal sensations, as predicted by the Outdoor Thermal Comfort framework (Figure 4.1). Thus, the context in which these assessments were obtained must also be examined.

A concomitant hypothesis to explain the high level of comfort observed under varied PET may be drawn from psychological factors, namely the aesthetic experience and naturalness. As part of the same questionnaire, some perceptual qualities of the vegetated areas and of the streetscape were also probed. In particular, the planting's attractiveness and the aesthetic appreciation of the street both had high scores (1.26 and 1.51 out of a maximum of 2). It must also be recalled that about 15% of people questioned had changed their route to pass through the area, which is consistent with, and reinforces, the satisfaction respondents derived from the aesthetic experience of the street environment. From a statistical standpoint, these three measures are positively correlated to the ASV votes. A Spearman Rank Order Correlation test indicated that the weakest correlation was between "More of this type of greening" and ASV, $r_s = 0.11$, $p < 0.05$, followed by the attractiveness of the planting, $r_s = 0.20$, $p < 0.01$. The strongest correlation was observed with the overall aesthetic of the streetscape: $r_s = 0.25$, $p < 0.01$. All these correlations indicate positive influence of the place's aesthetic components on the reported thermal sensation.

Equally, two items that were part of the appreciation part of the questionnaires related to naturalness. Respondents were asked how natural they felt the greening intervention was and whether they would like to see more of this kind of intervention. The mean score for naturalness of the planting was 1.02. This item was positively correlated with the ASV: rs = 0.12, $p < 0.05$. Beyond asking how natural they felt the vegetation was, a question on the perception of the air pollution in the space was added. This was motivated by the perception that more natural environment are good at depolluting the air (Derkzen, van Teeffelen and Verburg, 2017). The air pollution improvement question received a mean score of 0.8 (out of 2) but was not correlated with the ASV. This may mean that it was either a wrong postulate, that perception of the air pollution is a poor measure of naturalness or that this form of vegetation (meadow-dominated) is not specifically associated with airborne pollutant capture and removal. It remains that one of the indicators of naturalness had a positive association with thermal comfort. If indeed, as Nikolopoulou and Steemers (2003) postulated, naturalness aids in the tolerance of discomfort then this would bridge the gap between expected discomfort (30% using the ATSI model) and observed (0.9% from the questionnaire).

There is but one psychological state that seems to tie these two perceptual psychological factors that relate to comfort levels in respondents. In Chapter 3, it was established that all probed perceptual qualities had contributed, to various degrees, to increasing respondents' positive psychological affect, as is expected when urban dwellers interact with more natural environments. Conceptually, this is most understandable for the aesthetic experience since it ultimately creates a feeling of satisfaction on the quality of the connection a person has with the space they are in. A Spearman Rank Order test showed a tenuous yet positive and statistically significant relationship between happiness and temperature perception (ASV) ($r_s = 0.11$, $p < 0.05$) but did not with any of the binned comfort indices nor the air temperature. This demonstrates that the physical reality (micro-climate) did not impact on respondents' moods but that there was a correlation between happiness and perception; the latter was shown to be rather positive irrespective of actual conditions. Thus, it may be hypothesised that, while the physical weather did not contribute to respondents' happiness, their mental state influenced their perception of the weather and their thermal comfort; a hypothesis which was also formulated by Knez and Thorsson (2008). This element may be indicative of a causal link between satisfaction derived from naturalness and aesthetic experience and thermal satisfaction. This suggests that a positive aesthetic experience within a greened urban environment creates an overarching feeling of satisfaction that feeds into the satisfaction with the thermal environment despite the latter not being, objectively, comfortable nor enjoyable.

4.9 Conclusion

Results from the calculation of the thermal comfort index, the PET, showed that conditions were rather cool for a summer but that they were also extremely variable within and in-between days. This resulted in a very wide variability of thermal conditions over the survey period. Two usual methods to derive the neutral temperature and thermal sensation scale were used. They were both flawed since they produced aberrant neutral temperatures so we resorted to utilising a third method, which was not reliant on normal distribution of the data. The ATSI method produced a more credible result whereby the neutral temperature was situated around 19°C and the neutral comfort bracket was from 14.4 to 23°C. This comfort zone placed 70% of the sample within comfortable conditions. However, the fact that 99% of the sample felt comfortable could not be explained by the objective index. Indeed, the linear regression showed that 40% of the ASV variation could not be explained by the PET and the ATSI method still left 30% of the sample outside of the comfort zone.

A first line of inquiry consisted in looking for signs of physiological acclimatisation. Climatic data from the month prior to the questionnaire indicated colder PET which seems to explain the reason for a shift towards “Warm” ASV votes. The amplitude of variations were also larger than during the survey period. This would be indicative of acclimatisation. By reducing sensitivity due to large amplitude, any smaller amplitude might be perceived as more comfortable. Incidentally, an augmenting PET, more in line with summer temperatures, might aid in matching the expectation of summer conditions with reality, hence increasing satisfaction with the thermal environment. These results are generally in line with previous findings that found that acclimatisation shifts sensation votes to be aligned with comfort indices and adjust respondents’ tolerance to match current thermal conditions and therefore lead them to report feeling comfortable.

A second line of inquiry was to look at the effect of the transaction with the meadow dominated vegetation. Among the dimensions probed in this regard, some could be related to aesthetic experience, a factor known to affect outdoor thermal comfort. Specifically, and since the data was available for these dimensions, the aesthetic appreciation and the naturalness of the scheme were considered. All the perceptual items related to these dimensions, except for the question on the improvement of air pollution, correlated positively with thermal comfort. It was proposed that these two factors might be linked to thermal comfort via a positive affect, a feeling of "happiness" and postulated that it increased the users' tolerance of thermal discomfort. As such, the positive affect derived from other perceptual cues seems to have driven respondents to feel more comfortable than could have been predicted from indices alone. This study reinforces previous findings that the aesthetic appreciation of a place has an impact on a person's perception of thermal comfort. Moreover, this study adds naturalness to the list of dimensions within "aesthetic experience" that fashion outdoor thermal comfort.

This works extends further the list of benefits humans may derive from urban naturalistic meadows. The previous chapter demonstrated that transaction with the green space improved psychological well-being and perception of the streetscape. This chapter correlated the presence of the meadow with intangible benefits in the form of increased tolerance to thermal discomfort. Thus, psychological adaptation to thermal discomfort may be added to the list of cultural ecosystem services delivered by urban meadow vegetation.

Chapter 5: Thermal preference, expectation and landscape preference

5.1 Long-term factors of thermal sensation

5.1.1 Introduction

The previous chapter consisted of a study of the immediate perception of comfort within an urban environment. Not only was a local thermal scale constituted, the influence of acclimatisation suggested but the role of perceptual qualities of the environment, and particularly of a meadow-dominated scheme, as mediators of an individual's thermal sensation was established. This chapter explores further the link between perception of a landscape, and notably along three main axes preference, aesthetics and naturalness, and thermal sensation. Effectively, this chapter focusses on some of the long-term factors of thermal comfort: thermal experience, preference and expectation and the existence of unconscious frameworks within people's minds regarding the thermal environment, the influence of the physical and climatic characteristics of their surroundings. This chapter's first aim is to discuss these aforementioned factors in the light of the available literature. Then, a visual questionnaire is used in order to explore the existence and interactions between thermal expectation, thermal preference and landscape preference.

5.1.2 Long term psychological aspects of outdoor thermal comfort

The sensation of thermal comfort is evidently influenced by psychological mechanisms (Nikolopoulou, Baker and Steemers, 2001; Knez *et al.*, 2009; Lenzholzer, 2010). While the full list of relevant concepts has not yet been established, Nikolopoulou and Steemers (2003) drew up a list of some of the components that influence perception of the climate. These include Naturalness, Time of Exposure and Perceived Control; which were classified, in Chapter 4, as immediate perception modifiers. But these authors have also included factors that have a relationship with a person's history and their prior experiences, namely Expectations and Experience. Figure 5.1 highlights the factors this study is interested in among the various elements of the presented Outdoor Thermal Comfort Framework discussed in the previous chapter.

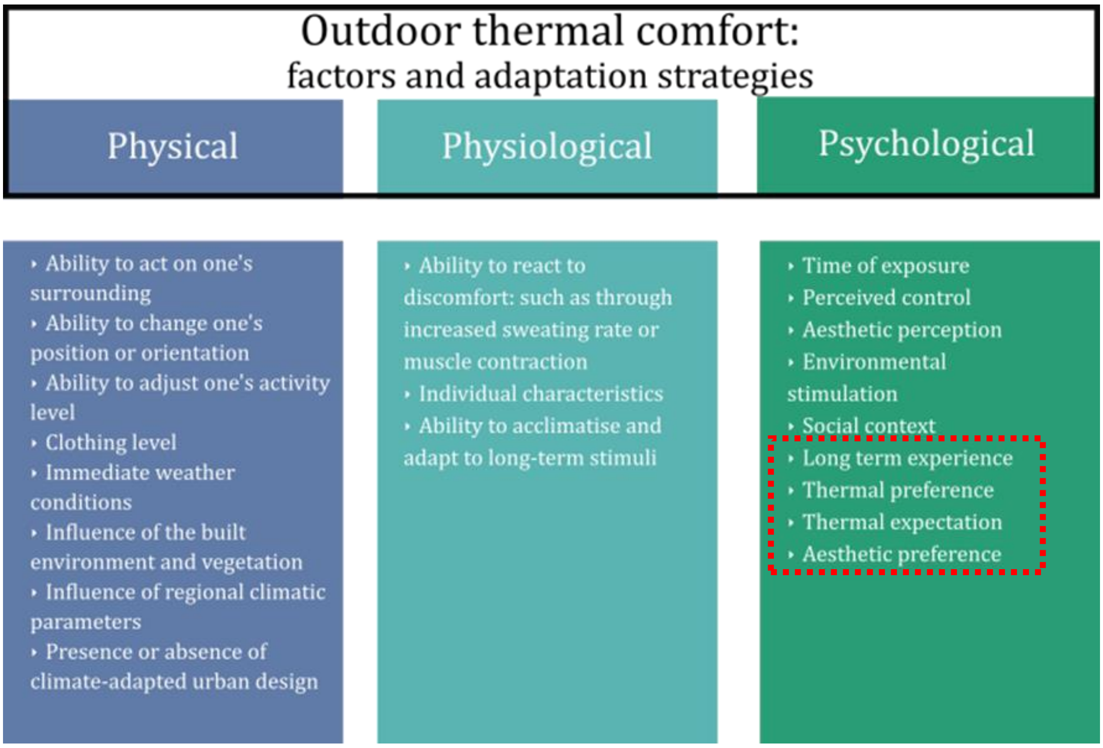


Figure 5.1: The Outdoor Thermal Comfort framework with the factors and adaptation strategies presented in Chapter 4. The focus of this present chapter is highlighted.

5.1.3 Thermal schemata: preference, expectation and long-term experience

Three factors related to past thermal experiences seem to emerge as long-term modifiers of one's thermal sensation: long-term experience that fashions thermal preference and thermal expectation. The role of past experiences via long-term memory on thermal expectation was notably spearheaded by Lenzholer (2008 & 2010). In a series of questionnaires within Dutch squares, she asked passersby to situate on a map where they expected uncomfortable and comfortable zones to be. Effectively, she collected cognitive maps that referred to engrained schemata within people's minds based on their prior experience with such areas and that shaped their *in-situ* expectations. Superimposing these expectation maps with real data, she showed that these expectations sometimes matched the present conditions but more importantly matched average climatic conditions and, at times, the space in which the worst of a negative conditions has occurred in the past. This way, the effect of long-term experience, which partly shaped expectations, was made apparent.

In a similar vein, Katzschner (2006) resolved the contradiction where people sought and placed themselves within seemingly thermally uncomfortable situation by demonstrating that very recent thermal history (coming from an air-conditioned building) as well as expectation of summer heat explained the search for exposure to the radiative heat even though shaded spaces were available. In this sense, urban dwellers preferred to feel warmer rather than be just comfortable. Thermal Preference is also observed as a function of country of origin (Nikolopoulou, 2004; Nikolopoulou and Lykoudis, 2006). In this sense, average seasonal temperature shaped what residents are accustomed to, have come to have preference for and what they expect at particular times of the year.

5.1.4 Aesthetic experience and preference

The perception of thermal comfort seems inextricably linked to where a person is and how this person connects intellectually and emotionally with this place (Knez, 2005). Hence, there seems to exist a connection between perception of the environment or urban setting and thermal comfort. This was made clear through the work of Klemm *et al.* (2015a) when preference for a certain street configuration, with front gardens and smaller trees, was judged more comfortable than another street with larger trees when mean radiant temperature would objectively give the latter as more comfortable. Contrarily to the approach taken by Knez *et al.* (2009), but closer to that taken by Lenzholzer, Klemm and Vasilikou (2016), we grouped these various factors as aesthetic experience and preference, knowing that such dimensions speak of the interplay between place, vegetation, urban infrastructure and a person's mind. In this chapter, aesthetic experience and preference encompass sensory (visual, olfactory, etc.), emotional and intellectual connection and perception on an immediate and long-term basis respectively.

Following the tripartite theory of aesthetics developed by Bourassa (1990), it may be said that a person's cognitive and affective response to a landscape or a place is the conjunction of three mechanisms. The "biological mode of experience" is the one particularly well described by Ulrich (1986 &1993) with notions of biophilia and biophobia and the evolutionary reasons for humans to deem certain landscape acceptable or not. In this mode, the subject taps into reactive, evolutionary reflexes. This may, for example, reflect the desire to have depth of sight and a feeling of security. This aspect of the appreciation and preference of landscape has been backed up by numerous environmental psychology experiments where subjects preferred savannah-like environments (Ulrich, 1993) for example or derived a sense of safety if space was opened despite a dense tree understorey in the background (Jorgensen, Hitchmough and Calvert, 2002). Incidentally, if this theory is widened to general perception of landscapes then Kaplan's Attention Restoration Theory (Kaplan, 1995) may be included alongside Biophilia since it predicts that some characteristics (such as diversity, depth of view and complexity) will be preferred on an unconscious, psychological, basis. The second mode of experience is cultural and responds to rules bound to social and historical context. It is for instance the thesis defended by Nassauer (1995) where she insisted on the role of cultural interpretation of the landscape, where there is a need to see human intention, the need for order and neatness shape a subject's experience of a landscape. It is evidenced perhaps by van den Berg, Vlek and Coeterier's experiments (1998) whereby they proved that the socio-economic background or the membership to a particular sub-culture shaped aesthetic appreciation. For instance, farmers rated landscapes with clear signs of agriculture (heavy human intervention) as beautiful which was at the exact opposite to cyclists who graded wilder landscapes as more beautiful. This cultural mode is bound to be more dominant within urban contexts (Home, Bauer and Hunziker, 2010). This set of rules is also what made uncertain the appreciation of the Grey to Green given its departure from "clean" landscapes with visible cues for care. The last mode of experience is the personal one. It is derived from a person's sense of self, identity and personal history. Riechers, Barkmann and Tscharntke (2016) highlighted the individual differences that may exist on the perception of the same green spaces, some may see a park as a meeting place some as a recreational space for their children. Interpersonal and intercultural differences are thus expected but a level of transcultural predictability may also be expected due to certain common biological determinants guiding appreciation and preferences (Home, Bauer and Hunziker, 2010).

5.1.5 Objectives and rationale for the questionnaire

Studies, summarised in Lenzholzer, Klemm and Vasilikou (2016), have started ascribing qualitative links between a given perception and some of the aforementioned factors. However, little, if any, have attempted to link them using a large sample in controlled conditions and using the classic tools of environmental psychology. The various elements highlighted in Figure 5.1 will be part of this study that will aim to describe the interactions between thermal preferences and expectations with regards to long-term experience. No methodology could be found within the literature on the manner to quantify an individual's thermal and climatic history; aside from field observation in the case of the immediate perception of comfort, such as in Katzschner (2006). In order to get a measure or an index of one's long-term experience, this research chose to use a surrogate named hereafter the Climate of Reference. The latter has been chosen to be the climate in which a person has spent most of their time in their lives or in recent years. We postulated that living multiple years in the same climate would allow for physiological adaptation. Additionally, through sensory experience and memory and aided by recurring weather phenomena, a psychological adaptation also ensues. Postulating that a person would acclimatise and come to mentally adjust with their own climatic conditions, we reduced a person's experience to the city and country they had lived most in. This in turn may be used to obtain the Koppen-Geiger climate code. While this method may be limited, it is an attempt at using an established climatic scale to describe what experience people may have. Combining this choice with our overarching aim of studying how landscape appreciation affect other perception, the various objectives in this chapter are :

- Evaluate the usefulness of a visual online questionnaire to uncover thermal schemata
- Evaluate the relationship between landscape preference and thermal perceptions
- Evaluate the relationship between thermal preference and thermal expectation
- Evaluate the usefulness of the Climate of Reference as a surrogate for long term experience

5.2 Methods

5.2.1 Photo-elicitation as a technique

This study uses photo-elicitation, a method that has been widely used within landscape and environmental research. Early on, it was used to get a basis of the biologically engrained, precognitive preferences of humans towards landscapes and what characteristics attracted us (Ulrich, 1986 & 1993). Closer in time, it has been used by Southon *et al.* (2017) as a means to gather people's views and preferences for different meadow planting style. Inversely, Kardan *et al.* (2015) used participant's rating of aesthetic preference and naturalness to search for the common characteristics of landscape that won participants' preference. And Kuper (2017) sought to use images with increasing levels of entropy and formal arrangement in order to understand the relationship between complexity and spatial distribution of landscapes and people's preference. If needed be, the power of images, particularly of those representing landscapes, to transmit pseudo-experiences has been proven by Lee *et al.* (2015). Their methodology experimentally proved that even a short, solely visual, exposure to a natural landscape mediated through the photographic medium meaningfully restored attention in test subject. This feature is expected, as part of Kaplan's ART (Kaplan, 1995), when the subject is placed within a real landscape but not necessarily exposed to a photographic rendition of one. In this sense, photo-elicitation has been proven to effectively do what it is designed to: provoke a responses, enhance memory retrieval, bridge physical and psychological realities and communicate a plethora of concepts otherwise hard to verbalise (Hurworth, 2003; Mathison and Hughes, 2012). In other words, it effectively allows the researcher to access a subject's schemata on a certain topic (Lapenta, 2012). This feature is of particular interest for the present study as the aim is to isolate long-term expectation and engrained evaluation within the respondent in order to bring out possible associations between thermal and aesthetic schemata.

5.2.2 Landscape scenarios

Choosing the landscape scenarios, and how they would differ from one another, to use for the questionnaire was arduous. Many elements have been associated with aesthetic evaluation of landscapes such as openness without too much exposure (Home, Bauer and Hunziker, 2010), complexity up to a certain threshold (Kardan *et al.*, 2015), naturalness, biodiversity for some and cues for human intervention for others (van den Berg, Vlek and Coeterier, 1998). Preference and use of a landscape are also affected by various levels of universal (Ulrich, 1986), cultural (Knez and Thorsson, 2008) and personal (Riechers, Barkmann and Tscharntke, 2016) biases. A facilitating approach was, instead, to consider landscape elements that were solely relevant to the urban microclimate realm.

The choice was made to use the Grey to Green as a base landscape scenario since it was in an urban setting thus eliminating the biases that may exist between a nature scene and an urban scene with natural components (Özgüner and Kendle, 2006). The chosen setting, as described in Chapters 2 and 4 is a low to medium density city centre with relatively low buildings and wide streets. The meadow of the Grey to Green has a diversity of species, colours and forms and was a highly appreciated vegetated feature (results from Chapter 3) for its aesthetics and naturalness, and it did not seem to exclude cues for care. All other landscape scenarios keep this scene as their base to keep the aesthetic perception of the street features constant. Coherence, which is understood as synonymous with unity (Kuper, 2017), is the property of a landscape to come together as an ensemble and give the eye directions to look into. In this work, coherence though linked to complexity, is kept as uniform as possible. The other vegetated scenarios added plants in the same pattern, as a planted allée, as per the original design of the Grey to Green, eliminating inasmuch as possible this as a cofounding factor of perception. Next, the vegetation's effects on microclimate had to be considered. This oriented the choice of increasing complexity and specifically geometric complexity of the scene rather than everything else. In most current studies attempting to relate perception to landscape element, complexity is reduced to the Shannon's Information Entropy (Kuper, 2017) or density of certain features like edges and pixel value histogram (Kardan *et al.*, 2015). Here, in a simpler fashion, complexity is understood as the presence of more types of plant forms that occupy more or less vertical space. We considered four levels of complexity: none (bare street), low (just herbaceous vegetation), medium (adding trees or bushes) and high (adding trees and bushes).

Increasing geometric complexity, effectively adding layers of vegetation, has a qualitatively predictable effect on microclimate. All vegetation provide some form of evapotranspirative benefit, potentially cooling the air in-situ in still conditions (Erell, Pearlmutter and Williamson, 2011). The sole addition of bushes can increase wind protection (at least from lateral wind), lower visibility (onto the road and opposite side of the street) but keep the canopy open to radiation. This scenario translates into a continuous vertical vegetation up to head height, creating an open green corridor. Adding only trees would decrease the radiation load received on the footpath by blocking overhead space, it would still allow for visibility at eye level and its canopy might mitigate winds at higher heights but not necessarily at dwellers' height. Adding both elements would block the most radiation and wind and, by filling all vegetation layers, block all visibility horizontally and vertically thereby creating a green tunnel.

As part of a collaborative effort, the scenarios were imagined and designed with Master's students who desired to further research in Grey to Green users preference. The first chosen landscape scenario was herbaceous vegetation ("Low only") that was modified from a base photograph of the Grey to Green to eliminate young trees planted in the background. Bushes were added to create the "Low & Medium" scenario, trees were added to create the "Low & High" scenario and both to make the "Low & Medium & High" scenario. The numerically added vegetation was taken from an existing database of high quality plant models and assembled using the software Adobe Photoshop. While the original photograph was furnished by the author, the manipulation was graciously undertaken by a fellow doctoral student, Mingyu Jiang. The images are shown in Figure 5.2 below.

5.2.3 Weather scenarios

As thermal preference is known to vary across seasons (Nikolopoulou, 2004; Krüger *et al.*, 2017), only one was chosen for all the items. The questionnaire was thus focussed on the summer as it is known in temperate climate or the hot season as it might be called in tropical climate and the base photograph chosen was meant to reflect this fact. The photo was taken around midday to make shadows obvious (photo-manipulation involved drawing shadows for the added objects). Two sets of binary descriptors were used: a set referred to the presence or absence of wind and the second set to the temperature being warm or cool. Given the assumption (made explicit to the respondents in the introductory comments of the questionnaire) that the hot season was being probed a third set of descriptor namely sunny and rainy was discarded. Early piloting work highlighted the difficulty of some respondents to project themselves into a set of climatic conditions with too many qualifiers and being repeatedly asked about them; a phenomenon of loss of attention of sorts. Additionally, the adjective “rainy” had the issue of not fitting with the visual information presented to the respondents. Hence, it was decided to narrow down the weather scenarios offered to participants to strict variants of a hot season, whereby “warm” was synonymous of a cloud-free day and “cool” referred to a cloudy day.

Figure 5.2: Base and manipulated photographs used in the online questionnaire. All situation show a sunny environment with increasing levels of vegetation. The original was taken by the author around midday in September 2017. The manipulation was done by Minyu Jiang, Ph.D. candidate in the Department of Landscape, University of Sheffield. It must be noted that the “Low only” scenario consisted in the removal of trees along the right side of the footpath. The author would like to express, again, its gratitude to Mr Jiang for his invaluable help.

5.2.4 Organisation of the questionnaire

After being given some contextual information about the questionnaire, respondents were asked about their age, gender and socio-economic status (full questionnaire in Appendix 2). More importantly, they were asked about the country and the city in which they have resided the most in the past. Then three items were asked for in the Landscape Perception section. Here, participants were asked which of four landscape scenarios they deem more aesthetically pleasing, more natural and which they preferred. Then their thermal preference was probed. This was undertaken by asking which form of urban landscape they would prefer being in given a set of climatic parameters. The same four landscape scenarios were proposed as above and a fifth choice "The other side of the street with no vegetation" was also proposed. The last section covers thermal expectation by asking from respondents to choose which urban landscape scenario they judge to be the warmest or most comfortable given two weather conditions. The answer choices were the same as in the thermal preference section.

5.2.5 Sampling and distribution of the questionnaire

The questionnaire itself was built using the online platform Qualtrics (Qualtrics, 2017). Distribution was made locally to University of Sheffield students and staff through a series of standardised emails and participation was encouraged with a prize draw. Ethics approval was received specifically for the online diffusion of the questionnaire and use of the data for the thesis and for publication. Written consent from participants was mandatory to complete the questionnaire (see Appendix 2). Diffusion was done exclusively through the internet. This mode of diffusion was chosen in the hope that respondents would answer it in a comfortable indoor situation. This controls for a variety of factors dealing with immediate perception that could potentially bias the access to generally held views, beliefs and perception about thermal comfort. To ensure each questionnaire was completely filled, each item had to be answered to before the next page could be displayed.

Minimum sample size was calculated for the descriptive part of the questionnaire that answers the question: "Is there an effect of thermal expectation on preference?". To do this, the choice of unordered categories (two times five landscape scenarios) created may be considered as the outcome of a dichotomous variable: “respondent chose the same landscape option twice” and “respondent chose a different landscape scenario in both questions” with respective probabilities of 20 and 80%. The null hypothesis would be that there is no effect of expectation on preference then by chance 20% of people would choose twice the same landscape scenario. The alternative hypothesis is: expectation has an effect on preference, hence more than 20% people would choose the same landscape scenario twice. Hence, given the table in Hulley *et al.* (p 91, 2007) for a descriptive study of a dichotomous variable and given a proportion of 0.2, taking the smallest width of confidence interval (W = 0.10) at a 95% confidence level, the minimal sample size should be 246 respondents.

5.3 Results

5.3.1 Sample description

The total amount of questionnaires collected was 585, of which 559 were completed, the unfinished ones were removed. 29 Respondents below eighteen years old were also removed from the data set. The valid number of questionnaires was hence 530. As shown on Figure 5.3, the most represented occupation is “Student” and the most represented Country of Reference is the United Kingdom. As shown in Table 5.1, 61% of the sample were women and 38% were men. The most represented age categories were the 18 - 25 years old followed by the 26 - 35 years old. All these numbers were to be expected since the distribution of the questionnaire occurred within an English university. Occupation, Country and Climate of Reference breakdowns are detailed in Figure 5.3.

Table 5.1: Description of the sample

Sex		**Age category**	
Male	202	18 - 25	372
Female	323	26 - 35	102
Other	5	36 - 45	28
		46 - 55	13
		56 - 65	11
Valid Sample	530		

The Climate of Reference of respondents was found using an extension of Google Earth Pro® that maps the current knowledge of the Köppen-Geiger Climate classification (Climate Change & Infectious Diseases Group, 2017). Each participant who completed the questionnaire had provided a Country and a City of Reference which were input into the program and the overlay of the climate map allowed to determine the Climate of Reference. The most prevalent one is Cfb, warm temperate with no dry season and a warm summer, (Kottek *et al.*, 2006; Rubel *et al.*, 2017). The two next most prominent Climates of Reference are Cwa, Warm temperate climate with dry winter and hot summer, and Af, Equatorial rainforest and fully humid, with 25 and 23 respondents respectively. It is interesting to note that the Cfb encompasses all respondents from the United-Kingdom, Ireland as well as a majority of Central Europeans and also niche geographical areas within Southern America and Africa, leading to this Climate of Reference representing about 66% of the valid sample.

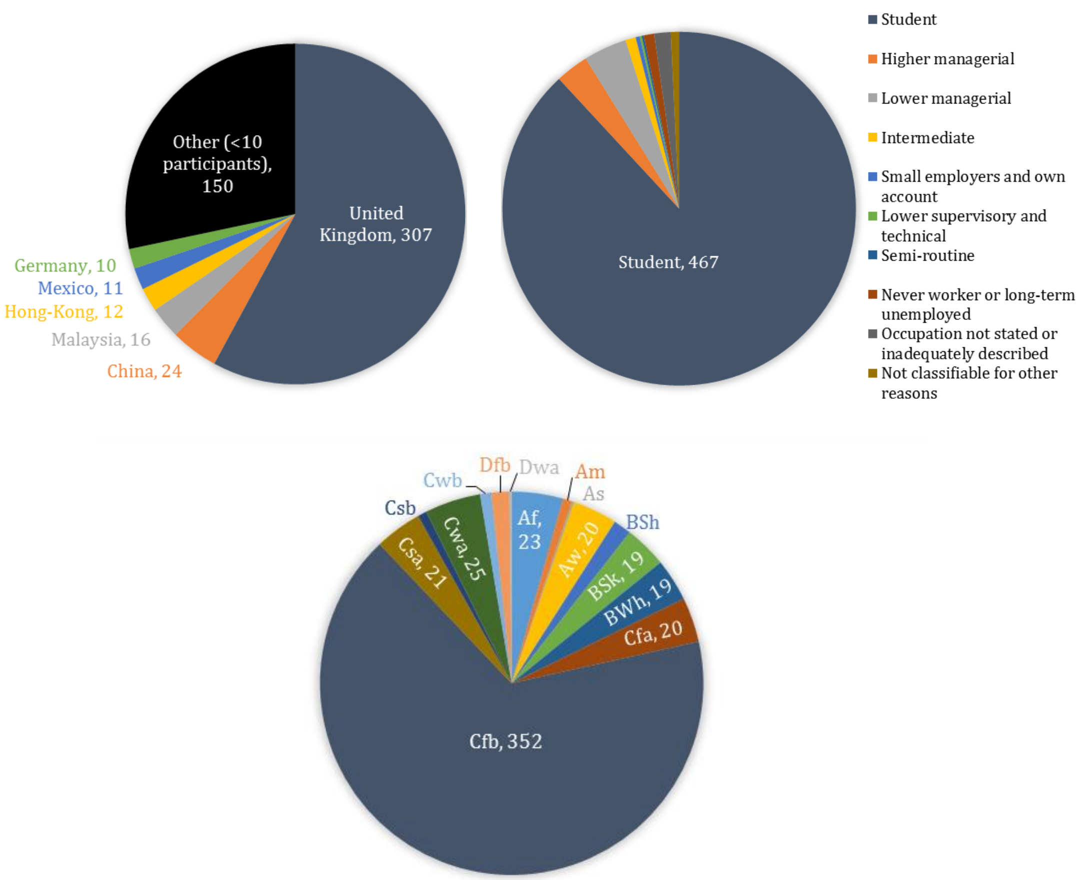


Figure 5.3, from left to right, top to bottom: Distribution of the Country of Reference, Occupation and Climate of Reference of the valid sample, 530 respondents. The most numerous groups in each categories are British (58%), Student (88%) and Cfb (66%). This is coherent with a distribution within an English university campus.

5.3.2 Landscape appreciation

In order to get a sense of how climate predicted views, preference and expectations the sample was divided into Cfb (66% of the sample) and non-Cfb (34%) respondents and compared to the whole sample. Figure 5.4 represents the distribution, normalised over a 100%, of the votes cast in each groups. The numbers in white within each category represent the actual number of votes casted.

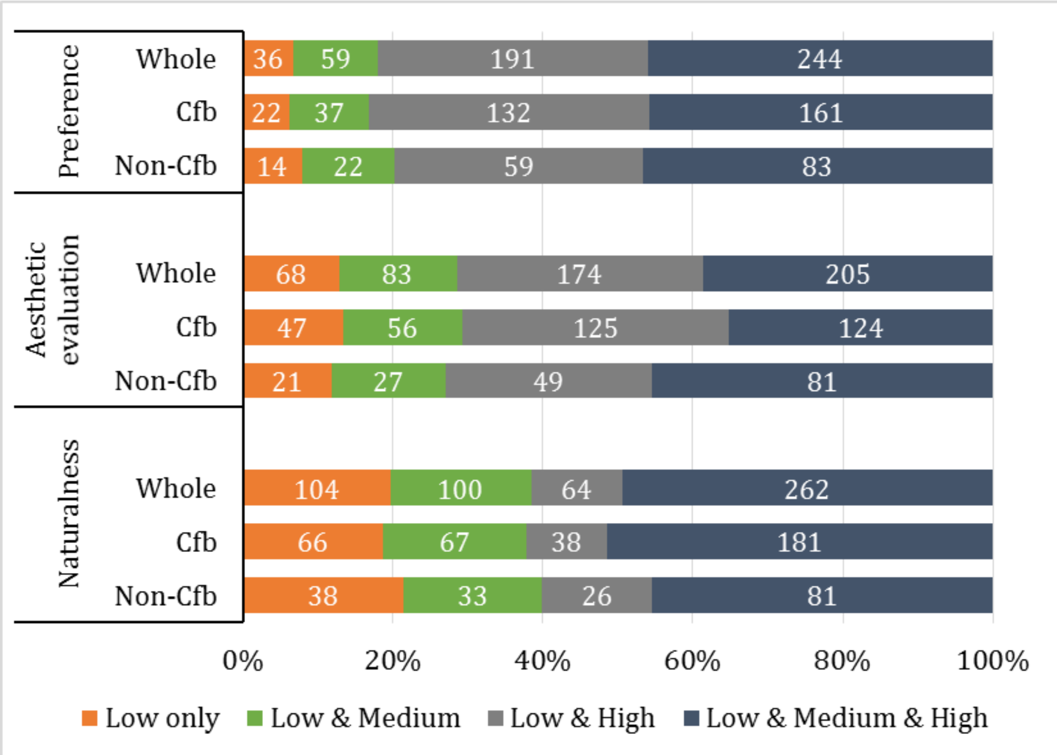


Figure 5.4: Distribution of landscape appreciation votes in the whole sample (n = 530), in the Cfb group (n = 352) and in the non-Cfb group (n = 178).

Among the four available landscape choices of increasing complexity, the sample preferred the most complex one which included trees, bushes and low growing vegetation with around 45 to 46% of the votes cast for this option. The second most favoured option was trees and low growing vegetation with around 33 to 37% of votes. The non-Cfb part of the sample preferred it less (33%) than the Cfb group (37%).

In terms of aesthetic evaluation, there seems to exist a difference that is probably attributable to culture. Indeed, the whole sample chose predominantly the most complex landscape, at 38%, followed by trees and meadow, at 32%, nearly in equal parts. For the Non-Cfb group, however, the majority still preferred all three layers (45.5%) but only half of this score preferred the combination (27,5%) of trees and meadows. It is interesting to note that the proportions of respondents deeming the “Low only” and “Low & Medium” in each category remains similar, around 27 to 29% with an approximately equal weight to each. In this instance, there seems an influence of culture in the distribution of aesthetic evaluation. Whilst in the Cfb group there is a nearly equal proportion for the two biggest choices, in the non-Cfb there is a disparity where the “Low & High” scenario only collects about a fourth of the votes while nearly half preferred the most complex scenario.

The evaluation of naturalness has a slightly different distribution. The most complex landscape was the most chosen with nearly half of the votes. Interestingly, “Low & High” was the category with the least amount of votes, 12% in the whole sample to about 15% in the Non-Cfb; in the latter case, the proportion of people deeming “Low & Medium & High” natural was correspondingly smaller. Unlike the other two other evaluation criteria, both “Low only” and “Low & Medium” had near-equivalent amounts of votes and cumulatively accounted for about 40% of the votes in all sample divisions.

5.3.3 Thermal preference

From then on, the questions included a “No vegetation” option. The first thermal preference question regarded which landscape scenario a person would prefer if the weather was still (no wind) and warm (i.e the highest possible radiative load, temperature and thermal stress). Unsurprisingly, as shown in Figure 5.5, as a whole, respondents preferred scenarios with trees, the most complex scenario being again the most popular choice (53%). Both lower growing scenarios received about 11% of votes each. The “No vegetation” was nearly absent in all groups. The most pronounced difference between sub-samples is the propensity of the non-Cfb groups for the “Low & medium & High” (62%) at the expense of all other vegetation scenario.

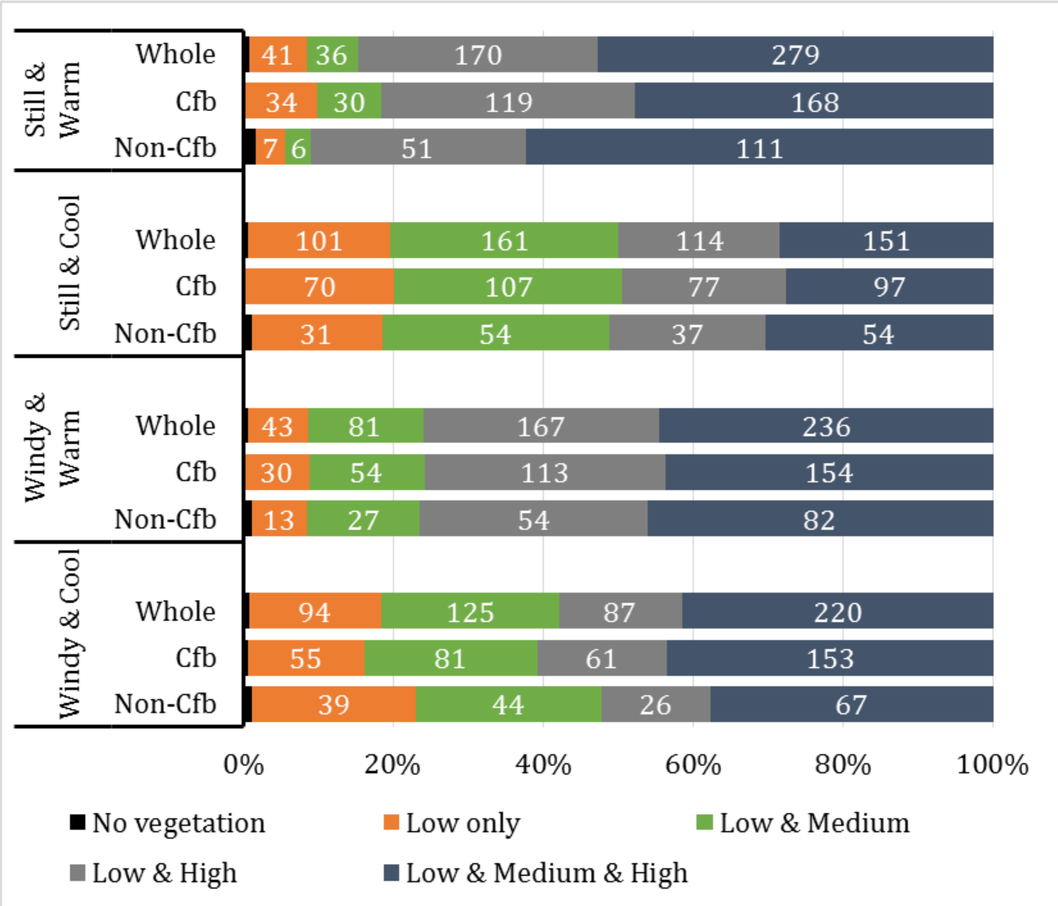


Figure 5.5: Distribution of thermal preference votes in the whole sample (n = 530), in the Cfb group (n = 352) and in the non-Cfb group (n = 178). Bar graphs indicate relative distributions and labels show the number of votes for each landscape scenario.

When asked about a situation with a “Still & Cool” weather scenario, the most preferred option was “Low & Medium” with about a third of the votes across the whole sample and all sub-samples. It is closely followed by “Low & Medium & High” with less than 30% of votes. The other two vegetated scenarios won around 20% of votes each. In a “Windy and Warm” situation votes went in ascending order of complexity with the most complex getting around 45% of votes. The two scenarios with trees cumulatively got 76% of all the votes. The results for the last weather scenario “Windy & Cool” are slightly more contrasted. While 38% of the Cfb group rated the two lowest option as desirable, there were close to 50% in the non-Cfb group. In both instance, however, the most complex option was most desirable with 43% and 37% of votes respectively.

It is interesting to note that overall proportions of preference for a certain type of landscape changes according to the weather scenario which the weather descriptor were successful and that indeed respondents could call upon different thermal schemata. The data suggests these schemata are primarily dominated by those concerning radiation and temperature. Indeed, the preference for the scenarios without trees jump between 40 to 50% when one of the descriptors is “Cool” and are around 20% or less when one of the descriptors is “Warm”. This entails that in a cool situation during the hot season a larger proportion of respondents would prefer being exposed to the sun. This is consistent with people seeking warmth during the summer, at least in Europe (Katzschner, 2006), particularly since they are expecting warmth so exposing themselves to sun would increase their feeling of warmth.

5.3.4 Thermal expectation

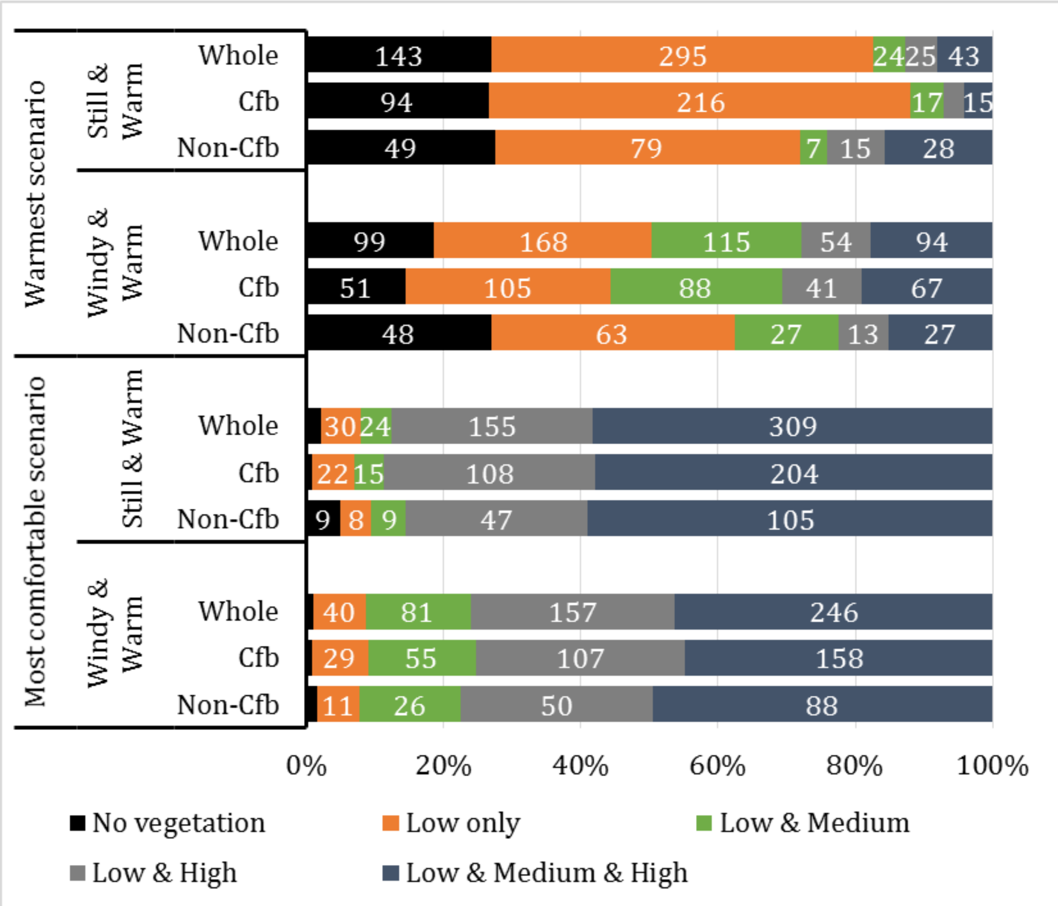


Figure 5.6: Distribution of thermal expectation votes in the whole sample (n = 530), in the Cfb group (n = 352) and in the non-Cfb group (n = 178). Bar graphs indicate relative distributions and labels show the number of votes for each landscape scenario.

In this section, participants were asked which landscape scenario they expected to be the warmest/most comfortable if the weather was either still or windy and warm (see Figure 5.6). For the "Still & Warm" situation, the scenario which was deemed the warmest was the "Low Only" followed by the lack of vegetation and the most comfortable scenario were the ones with trees, "Low & Medium & High" at 58% and "Low & High" at 29% in the whole sample. Respondents' expectations of the warmest scenario could be in line with reality since, all else being equal, the two most chosen landscape options are those who would provide the least radiative attenuation for human comfort. Indeed, in the case of a lack of greenery and lower growing vegetation, there is a lack of overhead canopy that would intercept solar radiation and hence decrease thermal stress. Inversely, the most comfortable situations are those that present overhead canopies hence providing radiation attenuation. These results strongly suggest that schemata associated with solar radiation exist, much like those associated with wind found by Lenzholzer (2010).

The "Windy and Warm" weather scenarios offer more contrasted answers. With regards to the expectation of warmth, the Cfb group judged the "Low only" scenario to be the warmest (30%) followed by the scenario with herbaceous vegetation and bushes (25%). The non-Cfb group voted the "Low only" and "No vegetation" scenarios as warmest (35 and 26% respectively). With regards to the "Most Comfortable" scenario if it was "Windy and Warm", the Cfb and non-Cfb groups agree with 45% and 49% of people electing the most complex scenario. Both groups then chose the "Low & High" group, scores of 30 and 28% respectively.

The "No vegetation" options has been chosen as one of the warmest options and was nearly absent from the choices of comfortable scenarios, instead the "Low & Medium & High" was the main option then. This expectation of comfort in relation to the presence of vegetation, and notably treed, vegetation reinforces the argument that people view green infrastructure as a more suitable for outdoor comfort in summer (Lafortezza *et al.*, 2009). There is also an understanding or at least a perception, that, in summer, the presence of plants do have an effect on the temperature felt in the street. It is intriguing how respondents, however, picked predominantly the "Low only". We cannot know if it is due to the perception that herbaceous vegetation will make the streetscape warmer or if the "No vegetation" was not picked due to it not having its own visual scenario.

5.3.5 Chi-square tests of association on personal variables and items

Using Pearson's Chi-Square tests with Cramér's V as a Post-Hoc indicator, the relationship between gender, age, Climate of Reference and the questionnaire items were investigated. For most items, there were no interactions between gender and responses. The exceptions were both expectation of comfort items, "Still and Warm" and "Windy and Warm" ($df = 4$, $p < 0.05$); both had low levels of interactions with a Cramér's V of 0.148 and 0.145 respectively. In the former case, more men thought they would be comfortable in the "Low Only" and less in the "Low and High" and in the latter case, less men responded "Low & Medium" but more "Low & Medium & High". It is unclear what these differences may mean as they do not seem consistent, it might be more due to a weak interaction of other factors such as preference or prior experience.

For age, interactions were detected in the expectation of warmth in the "Windy and Warm" weather scenario (χ (20) = 32.9, $p < 0.05$) although the interaction was weak, as indicated by Cramér's V: $\phi_c = 0.125$. The relative frequencies reveal that a larger proportion tended to think "Low & Medium & High" was warmer and that a larger proportion of older people deemed "No vegetation" and "Low only" warmer. These interactions may suggest that older people, with more thermal experience, perhaps judge more appropriately which situation it is going to be the warmest. This would be in turn imply that more experience leads to more refined thermal schemata. It could also be an artefact caused by the absence of visualisation for the "No vegetation" scenario and might just be indicative of differences in attention to the question and its options.

Lastly, a binary dummy variable was created to split the sample into Cfb and non-Cfb respondents and the same analytical method was applied. While no difference in landscape preference could be found, thermal preference of scenario when the weather is "Still and Warm" was found to have an association with the Climate of Reference (χ (4) = 17.8, $p < 0.01$, $\phi_c = 0.184$). In this case, the proportion of Cfb respondents was much lower in the "Low & Medium & High" category and higher elsewhere compared to non-Cfb. This might be due to lower summer temperatures in Cfb regions which leads dwellers to seek more exposure to solar radiation. The other associations were found in the Expectation section. The Climate of Reference influenced responses to the Expectation of Warmth on a "Still and Warm" day (χ (4) = 35.0, $p < 0.01$, $\phi_c = 0.258$). Indeed, the Cfb group voted more for the "Low only" category and less for the most complex vegetated scenario. Another association was found for the expectation of warmth on a "Windy and Warm" day (χ (4) = 18.2, $p < 0.01$, $\phi_c = 0.186$), however no clear trend could be found amongst the differences as they seem to be dispersed across the categories. The Expectation of Comfort in a "Still and Warm" weather scenario also indicated an association with the Climate of Reference (χ (4) = 10.6, $p < 0.05$, $\phi_c = 0.142$). In this item, it seems more non-Cfb respondents deemed the "No vegetation" scenario comfortable more often and less often the "Low & High".

5.3.6 Chi-square tests of association between preferences and expectations

According to Pearson's Chi-Square test, Landscape Preference and Aesthetic Evaluation were significantly linked ($p < 0.01$) even though not strongly ($\phi_c = 0.293$). Landscape Preference and Naturalness were not associated however. Indeed, regardless of preferred landscape scenario, respondents tended to deem the "Low & Medium & High" as the most natural scenario. Next, the relationships between Landscape Preference and Thermal Preference items were probed: all were significantly dependent. In the "Still and Warm" (χ (12) = 72.9, $p < 0.01$, $\phi_c = 0.215$), the proportion of votes for the "Low & Medium & High" increased at the expense of other categories indicating that more people preferred a fully shaded sidewalk under the highest heat stress. In the three other weather situations, the trends are similar with the treed scenarios losing votes to the non-treed versions. All three relationships were significant at $p < 0.01$ with ϕ_c between 0.165 and 0.231 indicating weak relationships between both.

In this section, the Thermal Preference items were tested against the Thermal Expectation items using the same weather situation. The landscape scenarios chosen in the Preference in the "Still and Warm" and Warm and Windy" items were significantly associated with those chosen in the Expectation of Comfort under the same weather situation. In the "Still and Warm" situation (χ (16) = 269.2, $p < 0.01$, $\phi_c = 0.358$), there seems to be a report of votes from lower growing landscape to higher growing ones. For instance, those who thermally preferred "Low only" expected comfort in the "Low & High" scenario and those who preferred "Low & Medium" reported their voices equally into "Low & High" and "Low & Medium & High". This indicates that, in the situation where heat stress is the strongest, respondents recognised, beyond their personal thermal preference, that adding trees would render the street canyon more comfortable. In the case of the weather scenario "Windy and Warm" (χ (16) = 181.6, $p < 0.01$, $\phi_c = 0.294$), the trend for this relationship is somewhat similar in its shift towards the treed landscapes yet less pronounced. This is coherent with the fact that on a windy day, heat stress would be decreased and such outdoor conditions would not be as uncomfortable and hence, more people would be comfortable across the board, hence would not deem a more shaded scenario more comfortable. There were no significant relationships between Thermal Preference and Expectation of Warmth.

5.4 Discussion

5.4.1 Appropriateness of the design and methodology

The notion that psychological factors are involved in thermal comfort has been recognised for a few decades (Fountain, Brager and de Dear, 1996). Yet, much remains to be understood as to precisely which factors, along with which spatio-temporal and perceptual moderators, ultimately influence the immediate sensation of thermal comfort (Lenzholzer, Klemm and Vasilikou, 2016). Some novel techniques have already been applied to understand thermal expectation and experience, such as the use of climatic mind maps (Lenzholzer, 2008). Here, we presented an online questionnaire that intended to isolate the postulated long term perception components that form part of the psychological factors of outdoor thermal comfort. To do so, four landscape scenarios were presented to respondents. These were in order of increasing structural complexity since the latter have predictable effect on the microclimate and hence on thermal comfort of pedestrians. By keeping the same base image, issues of naturalness (gradient of Nature: “hard” city to pristine nature) and coherence of the scene are kept equal. The online mode of distribution eliminated immediate perception factors such as having a choice of being there or being alone/with someone as well as all the factors related to the physical environment and physiological state and adaptation. Ultimately, photo-elicitation was used with the intent of singling the individual’s unmoderated long term preferences and expectation.

Despite uncertainties regarding the methods to uncover relationships between various thermal comfort factors, it shed light on a variety of dynamics. For instance, the expectation of comfort and warmth are two separate schemata as highlighted by their nearly completely opposite distributions. It also confirmed associations that were to be expected such as the association between the preference and expectation of comfort for a given weather scenario. The existence of associations between different Climates Of Reference is also encouraging as the latter might prove a useful approximation of the long-term experience factor for use in research. Response distributions being different between weather situations indicates the weather descriptors used effectively elicited different projections.

A limitation was revealed a posteriori by the surprising result that “No vegetation” was not the predominant choice for the expectation of warmth. In future research, the “No vegetation” landscape ought to be added as a visual choice for participant to choose from in all items. Prior research found that a purely urban scene was seldom preferred over vegetated ones (Ulrich, 1986), however providing the visualisation for other answers might orient better the respondents. Additionally, both the “Low & High” and “Low & Medium & High” scenarios have similar visual effects in the proposed landscape scenarios. Indeed, both the tall growing grasses and the bushes block the same portion of the field of view. While these two scenarios still differ by the type of vegetation, it does not translate well into a clearly demarcated use of space. This may have confused the respondents and explain a fairly high appreciation of the Low & High. It may be hypothesised that while it is not the most biodiverse scenario, it is, in the scenarios presented, as geometrically complex. This lack of clear difference between both scenarios may have affected the thermal preference and expectation as well. Providing improved visualisations would ensure that the different modes of response choice, photographic and textual, do not create observational artefacts. Overall, the methodology used by this study seems like a plausible research tool to study long term factors affecting outdoor thermal comfort granted the aforementioned refinements are added.

5.4.2 Urban greening strategies

The landscape scenarios presented to respondents increased in geometric complexity by adding more layers of vegetation to form a linear greenway within a low-medium density urban setting. A clear result from this study is the unambiguous preference of the most geometrically complex greening scenario which contained a combination of herbaceous plants, bushes up to head height and trees with higher canopies. In summer conditions, this dense vegetation would provide the greatest daytime radiation attenuation but night time temperature would be higher due to the reflection back onto the surface of outgoing long wave radiation by the canopy (Erell, Pearlmutter and Williamson, 2011). This result provides a contrasted contribution to landscape preference research. Predictably, the majority of respondents chose the most complex assemblage but this meant simultaneously choosing the most visually enclosed environment which is in contradiction with most landscape research thus far (Jorgensen, Hitchmough and Calvert, 2002; Home, Bauer and Hunziker, 2010; Ode, Hagerhall and

Sang, 2010; Kuper, 2017). This strongly suggest that there is indeed an influence of the setting on the mode of aesthetic experience (Bourassa, 1990). If landscape preference in the wild/in "nature" is guided by evolutionarily conserved biological predispositions (Ulrich, 1993) then the need for "extent" (Kaplan, 1995), which is absent in the "Low & Medium & High" scenario, is possibly overridden in an urban context. This phenomenon is further supported by the lack of association between naturalness and preference which is otherwise the case when respondents are confronted with "nature" scenes (Ode *et al.*, 2009). This lack of association suggests that preference was not guided by the "Low & Medium & High" scenario masking most of the buildings on either side of the walkway. Alternatively, the gap left between the canopies of the bushes or the grasses and that of trees (visible in Figure 5.2) was deemed giving enough visibility onto the surrounding areas to provide a sense of visibility.

Two additional trends are worth noting within the sample. Overall, the proportion of votes in the "Low only" increased from preference to aesthetic evaluation and to naturalness indicating the meadow alone or meadow and bushes were the least preferred and yet considered decently natural. The "Low & High" followed the reverse pattern, while consequently preferred it was deemed the least natural feature. This is surprising when considering that conventional parks and green spaces are characterised by trees and expense of amenity turf (Dunnett and Hitchmough, 2004). This result suggests that respondents that are accustomed to these landscape arrangement might still not deem them as "nature". This is in line with Özgüner and Kendle's (2006) findings on the public's aptitude to discriminate between "nature" understood as informal, lacking cues of human design, and "natural" as opposed to urban.

Landscape preference was significantly associated with all the thermal preference items indicating a relationship between the aesthetic experience and the thermal sensation. While this relationship has been qualitatively discussed elsewhere (for example in Nikolopoulou, 2001), here the relatively low Cramér's V (around 0.2) suggest that the Aesthetic Experience of the landscape while meaningful is only one of the factors of the psychological evaluation of thermal comfort. It is however clear that adaptation to the actual weather conditions happen. Indeed, there is a clear increase in votes for lower growing vegetation when the weather description included "Cool", i.e. a sky with clouds. It must be noted that the "Wind" descriptor did not seem to have an equivalent adaptation strategy, as no major systematic differences between the two windy and the two still scenarios may be found. This may be due to solar radiation being a more important component in outdoor thermal comfort, a conclusion supported by the RUROS study in their calculation of the Predicted Mean Vote as a function of climatic parameters (Nikolopoulou, 2004). It is thus interesting to simultaneously observe the expression of a thermal schemata, which comprises information related to, or is affected by, the aesthetic experience of the landscape while the subject retains some form of adaptability in response to discomfort.

Additionally, a caveat of this research is that respondents were not offered a neat or tidy alternative, let alone different design approaches, but rather an increasing amount of layers and structural diversity instead. This may be the reason why the results of this study differs from Zheng, Zhang and Chen (2011) which found that aesthetic appreciation was tied to neatness in urban settings. However, these differences in results may be due to culturally specific differences in appreciation. Our results overlap, however, in that aesthetic evaluation and landscape preference are higher when trees are present. This possibly points to the existence of a pan-cultural preference trait given that the Cfb sample behaved similarly to their Chinese sample.

5.4.3 Thermal expectation and preference

In addition to predominant landscape preference votes, treed scenarios were thermally preferred and deemed most comfortable when the weather descriptor included "Warm". As pointed out earlier, the existence of thermal schemata that are situation dependent is proven by our results. Another straightforward example comes from the different proportions of votes between Expectation of Warmth and Expectation of Comfort items. In the former, the most exposed landscapes are expected to be warmer and they are expected to be the least comfortable. Expectation of Comfort is associated to both Thermal and Landscape Preferences. In the former case, it suggests a link between what thermal conditions are preferred and which are deemed comfortable, it does not however provide a directionality to this relationship.

Using this set of questions, an adaptation to the wind factor has also been uncovered which joins Lenzholzer's (2008) conclusion that thermal schemata includes wind. Indeed, comparing both of expectation of comfort items, the proportion of the most complex scenario decreased in favour of grasses with or without bushes. This shift towards more open landscape may be explained by the fact that the wind provides cooling benefits and thus could counter-balance the discomfort caused by intense solar radiation during summer and thus a reduced need for overhead protective cover.

5.4.4 Influence of the Climate of Reference

In this study, the long-term experience of a subject was reduced and expressed by the Climate of Reference, subordinated to which country and city a person had spent most of their time in. The sample was mostly comprised of people whose reference climate was Cfb (66%), of which most were in the United Kingdom. Associations with Climate of Reference were found in the "Still & Warm" thermal preference and expectation of comfort and with both items of expectation of warmth. In the thermal preference's case, Cfb's proportion were close to their landscape preference while the non-Cfb shifted much more towards the most complex scenario. The Cfb group focussed their votes on the absence of vegetation and the herbaceous scenario more than the non-Cfb in the "Still & Warm" expectation of warmth. In the "Windy & Warm" expectation of warmth, these two choices were significantly lower than in the non-Cfb group. These differences of the expectation of warmth are perhaps most telling of a difference of experience. In the Oceanic climates, summer air temperatures are warm but not hot (Rubel *et al.*, 2017) and thus do not produce high heat discomfort, however wind might produce slight cold discomfort, even in summer. This would explain the fact that more Cfb judged the low growing or lack of vegetation as the warmest in still conditions but much less so in windy conditions.

These observations should, however, be used with caution. Firstly, if people that responded "No vegetation" (3 in Cfb and 9 in non-Cfb) in the expectation of comfort in "Still and Warm" conditions are removed, then the association is not present anymore. This indicates that abiding by the rule of no-less than five observed cases per cell then the association is non-existent. The conservative conclusion that we take is that this result is a statistical artefact. Secondly, differences in Climates of Reference, expressed, in the Independence Test, using a dummy variable, are not accurately depicted. Indeed, the non-Cfb group is a collection of reference climates grouped together due to their low occurrence. Hence, non-Cfb is a heterogeneous outgroup rather than a true comparison group. Similarly, the Cfb group included a majority of respondents which Country of Reference was the United Kingdom. Hence within the Cfb group, no valid comparison of responses could be made using the country of reference. Future research should seek sufficient amount of respondents from different Climates of Reference in order to test further how climatic experience shapes thermal expectation and preference. Despite these shortcomings, it may be concluded that the Climate of Reference seems to influence the long term perception of thermal comfort, through notably the development of schemata that deal with solar radiation and wind.

5.5 Conclusion

The main objectives of this chapter were to investigate the existence of engrained schemata related to solar radiation and wind, explore the interactions between landscape preference, thermal preference and thermal expectation. From a methodological standpoint, this chapter aimed at gauging the usefulness of a visual questionnaire to explore long-term components of thermal comfort.

From a landscape perspective, it has been confirmed that people preferred the most geometrically complex scenarios, which contained trees, bushes and grasses, even though it reduced the visual extent within an urban environment. This landscape scenario was also deemed the most aesthetically pleasing and the most natural. The landscape preference results support Bourrassa’s tripartite theory of aesthetics since it seemed that preference was pan-cultural and yet moderated by context. It has been proven that photo-elicitation, alongside iconographic and textual weather descriptions, allowed the effective retrieval of schemata for solar radiation and wind as respondents adapted their answers to fit the weather scenario presented to them. Similarly, thermal expectation and preference have been proven to be separate factors or moderators, as predicted by the Outdoor Thermal Comfort framework. Additionally, the present research proves that landscape preference is linked to thermal preference, as hypothesised, but not to thermal expectation. Thermal expectation, however, is associated with thermal preference. The reduction of one’s thermal history seems to be reasonably well estimated by the Climate of Reference, which was defined as the Koppen-Geiger climate (obtained via the city and country of origin) a person has spent most time in.

Chapter 6: Combating UHI using meadow vegetation: a yearlong comparative study

6.1 Introduction

This body of work has, so far, presented results that indicate that urban meadow vegetation delivers cultural ecosystem services as seen through the transaction with the green space and thermal comfort research approaches. As introduced, the delivery of regulating ecosystem services is now examined. These services cover the impact a living community and its physical environment have on climatic, hydrological and biological processes (Millennium Ecosystem Assessment, 2005). These may include, for example, water filtration and retention or pest regulation. The third research approach used in this thesis is vegetation’s effect on microclimate. Vegetation, by offsetting the inherent heat accumulation within cities, have the potential to make urban outdoor and indoor spaces more liveable. It is however unknown how much of an impact geometrically diverse herbaceous vegetation have on microclimate and thus on improving the liveability of cities.

6.2 The Urban Heat Island effect

6.2.1 Definition

The Urban Heat Island (UHI) effect is a well-defined phenomenon by which the urban fabric of town and cities heat up much more than the neighbouring countryside (Roth, 2013). This process, which is particularly observable during the late period of the day and into the night, stems from three main shifts in the properties of the physical environment. Urbanisation usually entails the laying down of man-made material that may have different optical properties to the natural layers they replace (Kleerekoper, van Esch and Salcedo, 2012). The primary change comes from a modification of the albedo, the ratio of radiation that is reflected to that which is absorbed by a surface, also understood as the percentage of reflected radiation. Effectively, this is usually a measure of reflectance in Shortwave Radiation (SWR) or solar radiation. While most grasses and trees have an albedo of between 0.15 and 0.30 (Ramirez and Muñoz, 2012), the albedo of artificial materials vary from 0.05 for the darkest asphalt to 0.9 for highly reflective paints applied on buildings. Most commonly, however, introduction of these artificial materials will reduce the overall albedo which, in turn, leads to a greater absorption of SWR leading to an immediate imbalance in the energy budget of the urban environment.

The second consequence of the change in material properties is the modification of the thermal properties. Vegetated areas, or open water bodies, mitigate higher temperatures by allowing liquid water to evaporate and plants to release water vapour, effectively permitting the transformation of the incoming radiative energy into the chemical energy necessary for the water to change phase. This process is limited to a momentarily existing water film of stormwater after a rainfall event on the impermeable surfaces used in the urban domain (Erell, Pearlmutter and Williamson, 2011). This lack of evaporative cooling is accompanied by such processes as heat storage in the surfaces and objects of a city. In practice, this translates into an overall increase in the specific heat capacity, defined as the amount of thermal energy needed to raise or lower the temperature of a kilogram of a material. Common construction materials tend to have higher specific heat capacities than the natural environment they replace (Roth, 2013). This leads to a larger heat storage and slower release of heat well after sunset.

The third main shift in properties is geometrical. On Earth, another major component of the radiative budget is the release into the atmosphere of Longwave Radiation (LWR). The latter is situated in the Infrared spectrum (Rogalski and Chrzanowski, 2014) and it allows atmospheric, surface and sub-surface systems to cool down after being heated up by incoming SWR. Temperature loss is rapid in natural environments but it is not in urban areas (Erell, Pearlmutter and Williamson, 2011). While heat capacity may have its role to play in this phenomenon, another consideration must be given to the geometry of cities. In the latter, the height of building that are often clumped together causes the emitted LWR to be reabsorbed by nearby surfaces (may they be vertical or horizontal). Coincidentally, this process is also relevant to SWR whereby building and ground surfaces reflect solar radiation that then may be reabsorbed by other nearby objects leading to smaller amount of SWR radiation actually reflected back into the atmosphere. Such a phenomenon is dictated by the geometry of cities such as the height to width ratio (H/W) of streets and the density of buildings (Smith and Levermore, 2008). Reabsorption of SWR and LWR leads to a consequential heating up and heat storage within the urban fabric that will have more difficulty being evacuated, the accumulation of which causes to the UHI.

A fourth factor that is also applicable to cities is perhaps less related to their physical characteristics and more to social factors. Indeed, other processes which variably affect the temperature of cities are the release of anthropogenic heat as well as greenhouse gases. Due to a concentration of human activities and dwellings within cities, and expectations of modern comfort and industrial needs, there exist a concentration in the use of cars, thermoregulatory systems (for heating or cooling), machinery for production and fossil fuel consumption to power all these items (Smith and Levermore, 2008). All these factors, amongst others, contribute to the direct release of heat locally as well as the emission of carbon dioxide and pollutants, some of which are known to interact with the earth's radiation budget by notably reflecting outgoing LWR back to the surface (Kleerekoper, van Esch and Salcedo, 2012). While the contribution of these processes to the UHI is variable and debated, it is undeniable that they interact with the radiative balance of cities (Erell, Pearlmutter and Williamson, 2011).

6.2.2 Surface and air temperatures

The UHI may be studied from two complementary angles. Using the atmospheric temperature, which is the most commonly mentioned, research has found an air temperature (T_a) difference between the city and neighbouring countryside. Using surface temperature (T_s), it is possible to observe that the man-made materials themselves heat up and store energy much more than natural surfaces. There is, of course, permeability between both variable as radiative and convective (i.e. via the movement of air and local conduction) heat exchange occur between them, rendering them interlinked. The air temperature component of the UHI is theoretically understood as being most visible at night and being present in radial patterns centred on the city centre but dipping in areas with natural features (parks or open water bodies for example) and has been confirmed even in temperate climates (Skelhorn, Lindley and Levermore, 2014). It is however arduous to predict accurately its nature given that the air has fluid properties and is therefore affected by the geometry of the street as well as the local weather, but more importantly by the wind patterns and speed created by the mesoscale climate and 3D configuration of said urban fabric. Air temperature is known to vary, even at the scale of a park (Jansson, Jansson and Gustafsson, 2007) or in the surrounding of a single tree

(Shashua-Bar and Hoffman, 2000). Moreover, it exhibits different properties whether the Canopy Layer (up to the average height of buildings) or the Urban Boundary Layer (up to ten times the average height of building) is considered. It could therefore be considered a less reliable indicator of the UHI as its surface counter-type. For instance, Smith *et al.*'s (2011) comprehensive work using both ground based mobile sensing units (mounted on cars) complemented by airborne transect measurements in the city of Manchester (UK) yielded a good correlation between T_s and surface cover type (residential, industrial etc.) but only a poor correlation could be obtained with T_a. This is even more relevant in the city in which this study is taking place, Sheffield (Cfb in Köppen-Geiger Climate Classification), since it is commonly windy with monthly means of 8 to 14.5 $km.h^{-1}$ (Sheffield Weather, 2017) and frequently occurring high gust speed. For this reason, the present study is primarily concerned with surface temperature which depends more on the Sky View Factor (the degree of openness) and type of land use and cover.

6.2.3 Plants to combat UHI

Plants are known to provide microclimatic regulating ecosystem services (Smith and Levermore, 2008). These notably happen thanks to evapotranspiration which is the combined process of evaporation that takes places on the surface and in the soil and transpiration whereby plants excrete water vapour through their stomata. In the altered heat balance that takes place in the urban environment, vegetated areas have the unique ability to effectively cool down their immediate surroundings. They achieve this through, notably, the aforementioned phase change heat transfer; which is the case where solar radiation's energy is used to make water change from a liquid form to its gaseous phase. Effectively, vegetated areas allow the creation of latent heat rather than sensible heat (Snir, Pearlmutter and Erell, 2016), hence providing climatic regulation for the benefit of local environment and city dwellers.

The other mechanism by which plants provide a climatic benefits is through shading. In this regard, trees are often considered to have an appreciable effect on air and surface temperature. Shashua-Bar and Hoffman (2000) noted that single trees can reduce the surrounding air temperature by up to three degrees Celsius in an arid climate. Sanusi *et al.* (2017) offered a more nuanced narrative by finding that air temperature in the vicinity is dependent on the "Plant Area Index" (an estimate of canopy density) and tree morphology. Incidentally, these results, which were obtained in another Cfb region, indicated that in the early morning the air temperature beneath the tree was slightly warmer but there was a definite reduction of a degree from 12:00 to 16:00. They did, however, notice a significant reduction of the PET, which also takes into account radiation, of the order of five degrees and hence an increase of summer thermal comfort. The efficacy of trees and shrubs in reducing sUHI was further confirmed by Edmondson *et al.* (2016). They found these types of vegetation were particularly efficient at reducing soil temperature at a depth of 1.5 centimetres and more so than mown grassland There is, however, a gap regarding the effectiveness of lower growing plant species that are not turf (included in such studies as Peters, Hiller and McFadden, 2011 and Armson, Stringer and Ennos, 2012) have on surface temperature.

6.3 Objectives and methods

6.3.1 Objective of the study

To achieve UHI combating services, notably through a reduction of the surface temperature, the vegetation notably needs to provide shade in order to attenuate SWR and hold water in order to transform sensible into latent heat. Prior research has shown the potential of trees in these regards (Edmondson *et al.*, 2016 for example) but it is unclear how other forms of vegetation may perform. The effect of herbaceous vegetation on surface temperature, UHI and thermal comfort is poorly documented. Existing studies have not reached a consensus regarding their effect (Snir, Pearlmutter and Erell, 2016). This is partly due to the difference in geographical location and climatic conditions of the different studies as well as differences of setting and types of herbaceous vegetation envisaged.

Grasses and forbs provide seasonal variety in colours and textures. Given their three-dimensional scale, they allow designers to deliver visual complexity and provide aesthetic fascination to humans (Dunnett and Hitchmough, 2004). Some ‘naturalistic’ planting designs require very little maintenance, making them a sustainable choice of vegetation. Since each individual plant take much less space than a mature trees, this type of vegetation offers the possibility to introduce many species within small spaces, effectively increasing biodiversity several fold more than their woody counterparts. Herbaceous vegetation may, in certain situations, be more appropriate than trees in street and urban open space design. One the one hand, trees may restrict airflow or create vortices in which airborne pollutants may accumulate and thus have adverse health consequences (Salmond *et al.*, 2016). On the other hand, grasses may serve as spatial separators and visual landmarks without clogging the sky view. While the absence of overhead canopy means less SWR attenuation, herbaceous vegetation, and meadows particularly, deliver a plurality of concomitant ecosystem services. In Chapter 3, it was established how users of the Grey to Green not only enjoyed the appearance of the scheme but also how it positively influenced their psyche. It was suggested, in Chapter 4, that the scheme also had thermal comfort benefits, mediated by this overall positive affect. However, it was unknown if herbaceous vegetation could also provide climatic regulating services.

To this end, the present study aimed at comparing the microclimatic benefits delivered by tall and dense herbaceous vegetation with that of trees and low-growing vegetation. The surface temperature of four different types of surfaces were monitored: a baseline concrete walkway, a densely vegetated meadow, turf underneath trees and exposed turf. The central question this study posed is: how does T_s under the meadow compares to that of concrete and shaded and exposed amenity turf?

6.3.2 Study site and method

Similarly to other chapters, the Grey to Green scheme was chosen as the study site. Two areas were identified, Figure 6.1 shows their location on the scheme and provides Google Street Views. Area 1 was towards the Western end of the scheme and includes a concrete and a vegetated surface as well as some turf underneath a row of mature trees. Area 2, situated closer to the Eastern end of the scheme, includes a concrete and a meadow covered surface but also an exposed section of turf. The central section of the scheme is next to two Justice Courts. As such, the City Council had requested that no measurements and no photographs be taken in their immediate vicinity. This is the reason for both areas to be on the extremities of the scheme and for the lack of measurement area in the middle of the scheme. The turf measurements (exposed and shaded) were added only later as Area 2's landscaping work advanced and exposed turf was installed. Prior to this, only the meadow and concrete surfaces were considered. Photographs of the vegetated surfaces in Area 1 and Area 2 are presented in Figure 6.2.

The meadow is characterised, as described in Chapter 2, by a wide diversity of species and growth habit leading to a geometrically complex multi-storey vegetation. It is installed in a bioswale with a growing medium that heavily favours drainage, being coarse and mostly mineral. It was unclear how the meadow might perform in the Grey to Green during hot summer days. Indeed, it was expected that the transpiration might become less relevant due to the rarity of water within the medium which might have an impact of T_s reduction. At the outset, it was equally unknown how the vegetation would perform in winter, whether it would further reduce surface temperature due to shading of the ground whereas the concrete would absorb most of the SWR thereby making the street slightly more comfortable or not.

A common tool in thermography studies is the use of satellite imagery, due to its ability to capture a wide area. However, these techniques are riddled with measurements uncertainties due to cloud over, atmospheric scattering and different land cover types below the pixel resolution (Chen *et al.*, 2017). This study used a handheld thermal imager (specifications given in Table 6.1) which permits an in-situ comparison at the micro-scale, more representative of potential effects on the local microclimate.

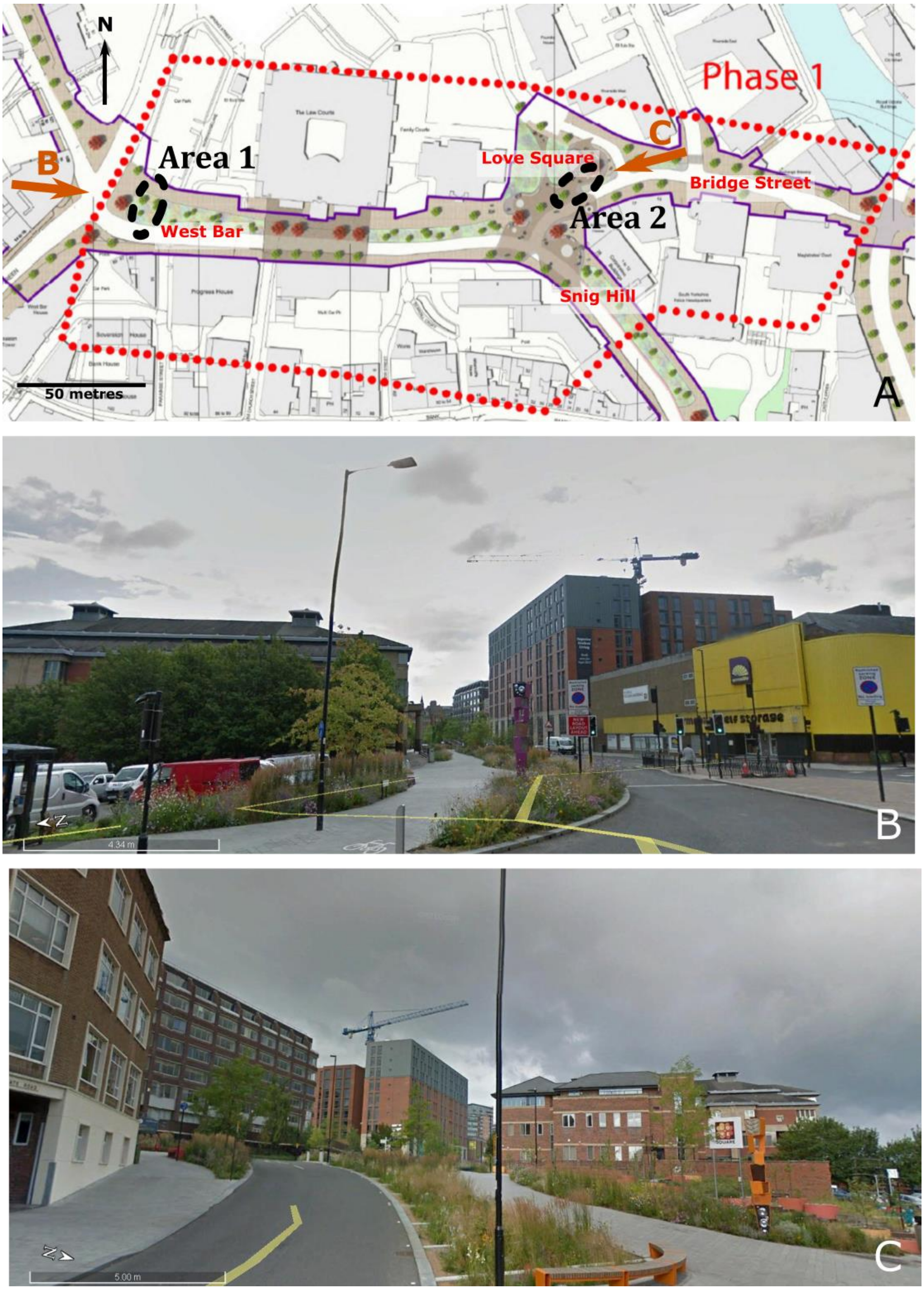


Figure 6.1: Map and views of the two measurement areas on the Grey to Green.
Even though the topography between both areas is slightly different and building placed differently, they remain in open urban settings with building heights being roughly the same.
A) Map of the Grey to Green with both Areas highlighted. The orange arrows point in the direction from which views B and C were taken (modified from Sheffield City Council material).
B) View of Area 1 (taken with Google Earth Pro).
C) View of Area 2 (taken with Google Earth Pro).

Figure 6.2: Photographs of the vegetated surface types considered in this study.
A) Meadow within the bioswale, Area 1. It shows the diversity of height, forms and shapes within the community leading to dense plant carpet
B) Turf present underneath a row of mature trees, Area 1. It shows the shape and arrangement of the trees' canopies.
C) Meadow vegetation within a bioswale cell with check dams on either sides, Area 2.
D) Exposed turf (Love Square), Area 2.
All photographs were taken by the author

6.3.3 Protocol

Twenty-four hours thermographic measurements were undertaken once a month, or twice at times. They were undertaken every two hours starting from 18:00 on the first day until 16:00 of the next day with the 04:00 slot omitted to allow the researcher to rest. Each measurement round was made in the same sequence for consistency. At the beginning of each campaign, Super 88 tape® was applied onto the surfaces and as per the literature it was assumed to have an emissivity of 0.95 (Fronapfel and Stolz, 2006; Ciocia and Marinetti, 2012). In accordance with thermal imaging protocol, the air temperature and relative humidity were input into the camera and the Apparent Reflected Temperature recorded and input. Three pictures were taken of each surface type in each area perpendicularly to the surface, at a height of around 1 metre. Planning for each of the measurement rounds involved attempting to avoid major rainfalls to prevent material degradation and major sunny days in order to avoid skewed measurements due to high background radiation. When such conditions were unavoidable, efforts were made to wipe the water from the tape or to temporarily shade the tape to let additional infra-red radiation dissipate (similarly to Armson, Stringer and Ennos, 2012). In parallel, iButtons were used to monitor local air temperature during these periods. They were placed in a single radiation shield at a height of 2 metres on the Northern end of Area 2, down the dominant wind in the area which is predominantly going towards the North–North East direction. Additionally, three underground moisture and temperature sensors were placed in Area 2, in the same bioswale cell on which surface temperature were taken. They were installed as per manufacturer's instructions (Decagon Devices, 2015 and 2016). All technical specifications for these equipment are reported in Table 6.1. Image analysis was conducted solely using the FLIR Tools software™.

Table 6.1: Specifications of the equipment used in the present study	
FLIR T420Bx (FLIR, 2013)	
Spectral range	$7.5.10^3$ to 13.10^3 nm (Long Wavelength)
Range	-20°C to 350°C
Accuracy	+/- 2% of Temperature reading
Sensitivity	<0.045°C at 30°C
Field of View	25° x 19° (minimum focus: 0.4 m)
DS1921G Thermocron® iButton (Maxim Integrated, 2016)	
Accuracy	±1°C
Resolution	0.5°C
Range	-40°C to +85°C
Sensing rate	Every 30 minutes
Decagon Em50 logger with 3 x 5TM sensors (Labcell Limited, 2015)	
Sensing ranges	0 to 100% Volumetric Water Content -40 to 60°C
Accuracy	± 3% Volumetric Water Content ± 1°C

6.4 Results

6.4.1 Soil moisture

While not the main focus of this study, soil moisture content and temperature were monitored for the duration of the programme. Three probes were placed in-situ, two at a depth of 5 cm and one at a depth of 20 cm. It was found that one of the sensors at 5 cm depth broke when inserted into the medium, its results were discarded, and hence Figure 6.3 is the result of two single sensors and not average values. At 5 cm depth, the minimum registered value was 0.046 $m^3.m^{-3}$ and the maximum 0.312 $m^3.m^{-3}$. At 20 cm, the minimum registered value was 0.058 $m^3.m^{-3}$ and the maximum 0.298. These empirical results would suggest a Field Capacity around 0.3 $m^3.m^{-3}$ and a Permanent Wilting Point situated around 0.05 $m^3.m^{-3}$. The presence of macro-particles within the matrix may explain lower minimum and maximum moisture contents, as they may increase hydraulic conductivity similarly to those reported in Poë and Stovin (2014). If indeed larger particles are prevalent in the substrate of the Grey to Green, this may lead to larger pore sizes which in turn decreases retention (Stovin *et al.*, 2015); which might explain the very low Volumetric Water Content observed in September 2016 and March 2017. Alternatively, these results could also be influenced by a lack of knowledge of the exact soil properties. No soil sample could be obtained to determine these quantities in laboratory. Hence, the probe could not be calibrated specifically for this custom-made soil that includes crushed glass and bricks as well as clay, sand and some compost and as such may only show slightly skewed results.

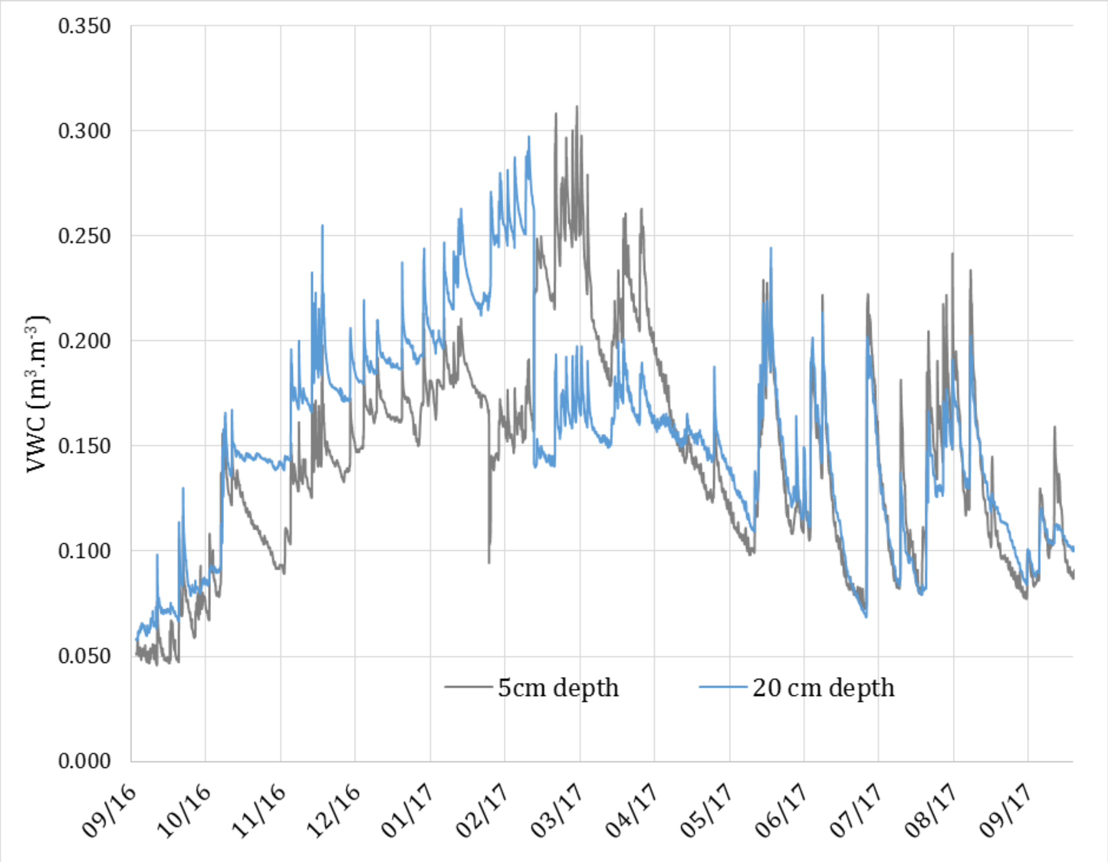


Figure 6.3: Volumetric Water Content (m^3.m^{-3}) throughout the outdoor campaign at two depths, 5 cm and 20 cm.

Overall, it can be seen that moisture gradually increased throughout September and October and momentarily peaked during mid-November. Water content was then high from mid-January to the beginning of March. After a significant drop, it peaked once in April. The trend was then on an overall decrease through spring and summer with brief spikes, presumably from short but intense rainfall event. To pursue this work further, calibration of the probe for the specific soil would need to be conducted then a comparison of rainfall events with water content evolution would provide quantification of the hydrological behaviour of the SuDS component of the Grey to Green.

6.4.2 Soil temperature

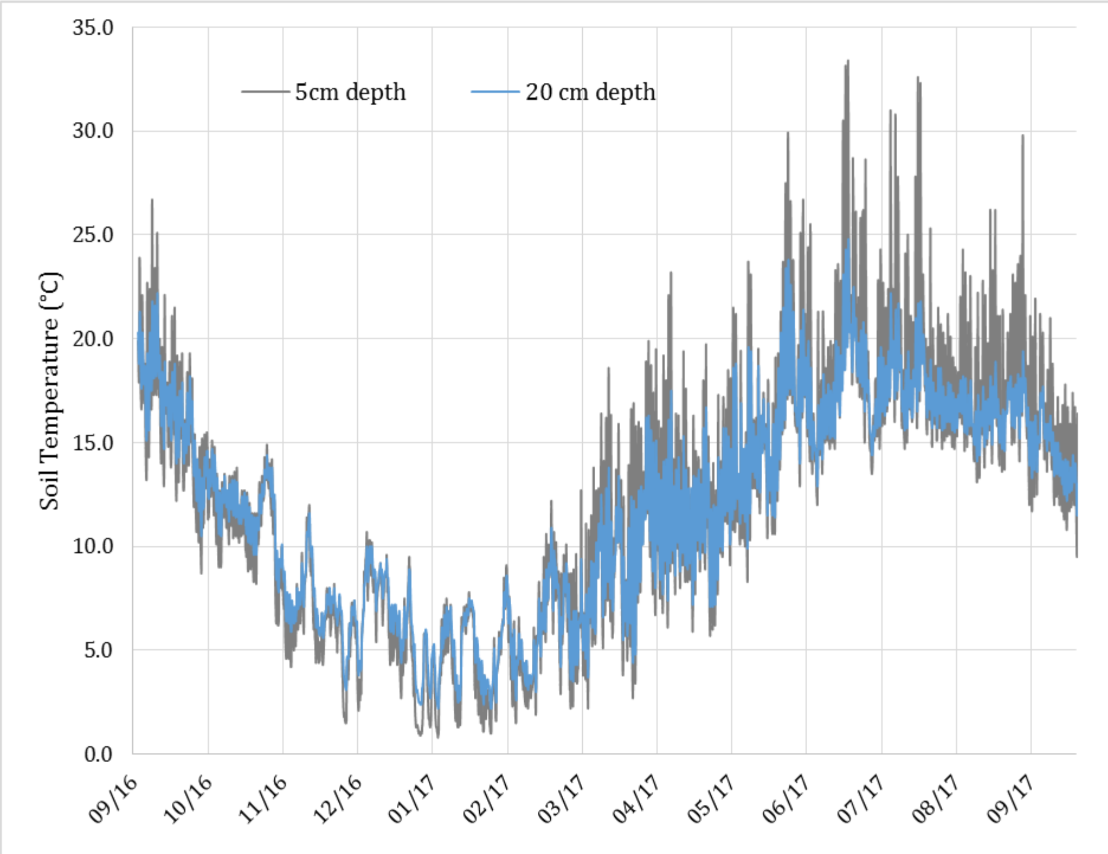


Figure 6.4: Soil temperature at two different depths throughout the survey campaign.

The minimum recorded temperatures were 0.8°C and 2.2°C at 5cm and 20 cm depth respectively; likewise maximum temperatures recorded were 33.4°C and 24.8°C. It is clear ground temperature follows the passing season with, seemingly, less variability during the winter and much more during the summer months. It is also clear, as expected, that the closer to the surface the probe was the more likely it was to vary whereas the deeper one was more stable and demonstrated less variability.

6.4.3 Air temperature

Air temperature (noted T_a) was measured on site via three iButtons positioned on the Eastern end of the bioswale (downwind of the main swale stretch) and the Reference air temperature was recorded using a weather station installed about a kilometre away from the site but with a similar cardinal orientation; the station being installed on the southern side of the building. The latter was on a rooftop at a height of approximately ten metres within a narrower and more built up urban canyon. Figure 6.5 shows the dates for which both the average iButton and reference air temperature data are available. Globally speaking, the lowest points for both locations is reached at 06:00. On site, the minimum air temperature was 1.8°C recorded at 08:00 on Run 8 (February) and the maximum was 25.3°C recorded at 18:00 during Run 13 (July). There is a clear seasonal trend of increasing average T_a as summer is approached then moved away from. It must be noted that these values are quite low. Only on seven occasions throughout these seven months did the temperature go above 20°C, indicating that Sheffield is in the lower bracket of the Cfb Weather (Kottek *et al.*, 2006).

It is clear that the site's T_a does not differ significantly from the Reference air temperature. A linear regression of both temperatures was performed to confirm that both variables are very closely linked with a coefficient next to one as seen below.
$Reference\ Temperature = 0.97 \times site\ temperature - 0.269$, $R^2 = 0.984$.
In general, the site's temperature was higher by an average of 0.7°C. Given that the iButtons used had an accuracy of ±1°C and that the weather station had an accuracy of ±0.5°C, this difference may be considered insignificant. The occurrence of absolute differences (0.1°C bins) between both sites is plotted in the bottom right hand of Figure 6.5. It can be observed that most differences are below 1.5°C which is still within the uncertainty range incurred by the accuracy of both instruments.

Similarly to Smith *et al.* (2011), the air temperature is not very indicative of the type of surface or urban environment being studied. Additionally, Sheffield tends to be a windy city, mixing within the Urban Canopy Layer is probably responsible for an equalisation of the overall air temperature. Even if the trend of lower canyon air temperature at the reference location is considered, the fact that it occurs from February until September points to the existence of systematic differences between locations. These may include the higher height of the weather station and bigger exposure to wind channelled through the canyon and shading from the other building at the reference location. This may be particularly true for the systematic differences observed at 18:00, 20:00 and 22:00 where the canyon seems cooler than the Grey to Green. The higher building on the other side of the street may shade the sensor or higher wind speed brings Ta down. On the other hand, the Grey to Green's sensors are fully exposed to sunlight and within a large open public space which may in turn decrease wind speed. As such no relevant effect of the Grey to Green scheme is observed on the air temperature.

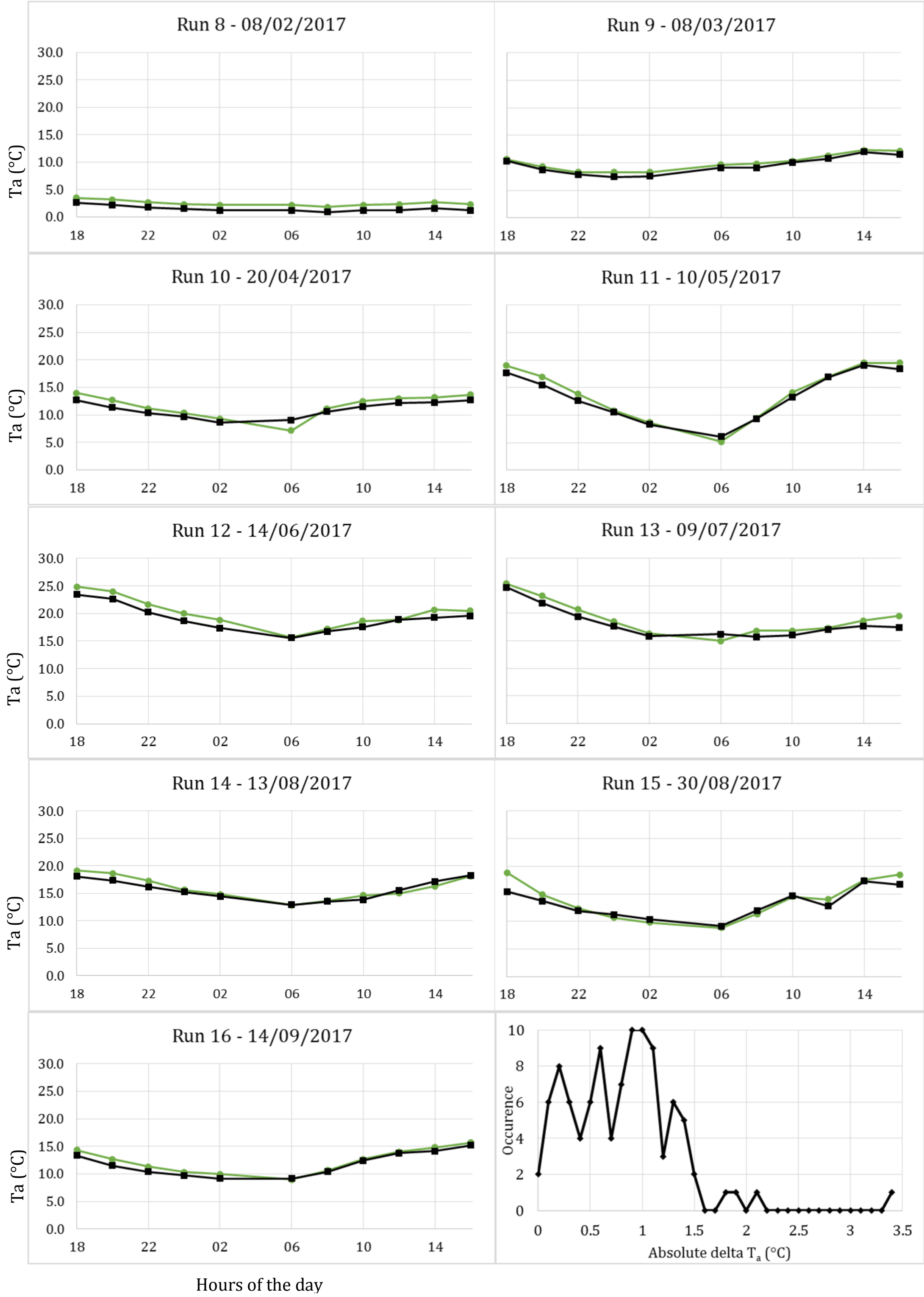
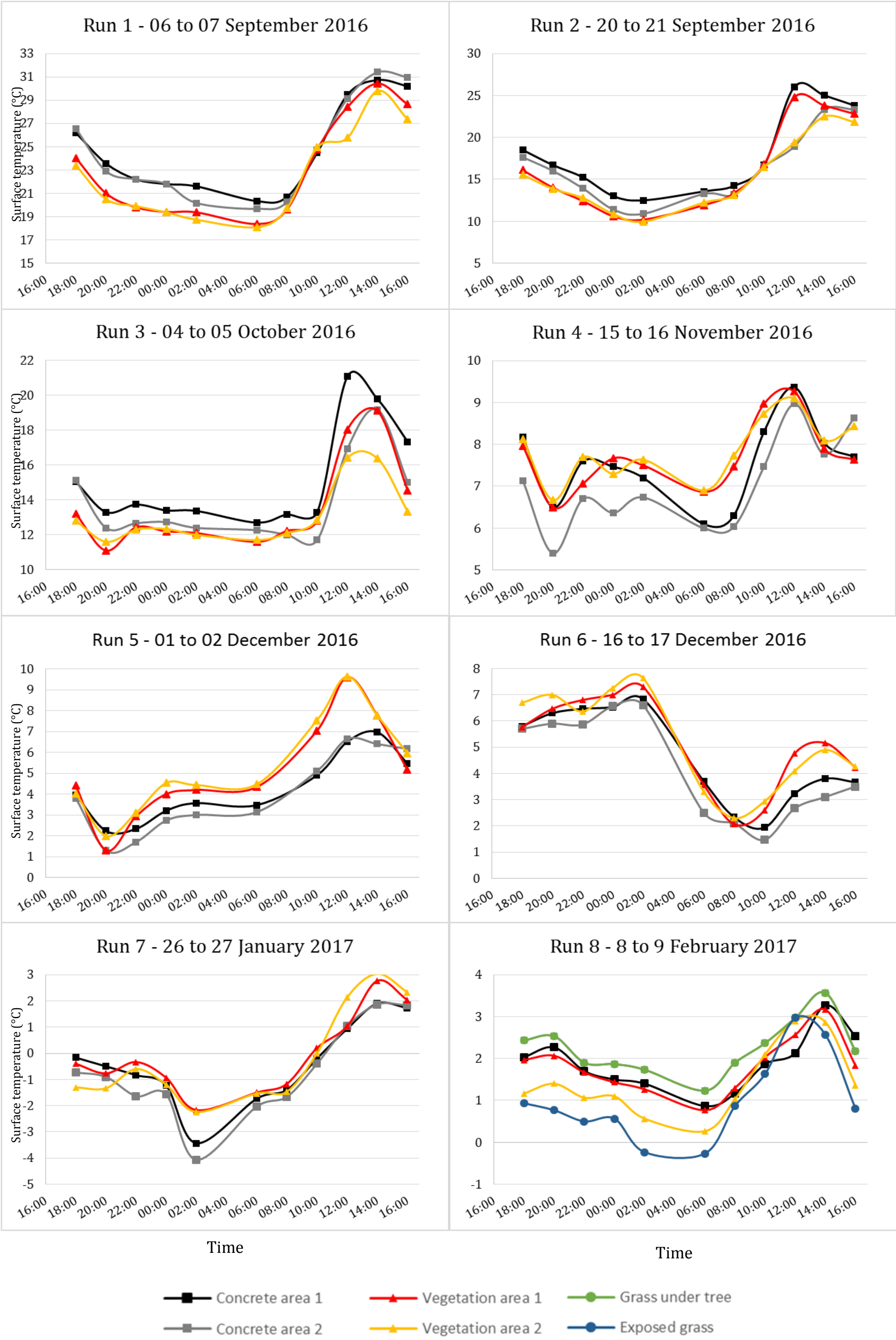


Figure 6.5: Air temperature (°C) on site with iButtons (green curve) and at a weather station on a nearby rooftop (black curve) in an urban setting. Bottom right: distribution of the absolute difference (°C, bins of 0.1) between on-site and reference air temperatures.

6.4.4 Surface temperature graphs

Figure 6.6 shows the data for each surface type in each study area. In Figure 6.7, the measurements from Area 1 and Area 2 for concrete and the meadow surfaces were averaged. This was motivated by the fact that both had slight differences in their degree of openness and what building surrounded them. Additionally, the surface cover of the meadows patches were slightly different. In Area 1, the plants were generally a little further apart whereas in Area 2, the swale cell was very densely vegetated. Averaging measurements thus reduces minor differences and is more representative of the impermeable and permeable surfaces as a whole. Concrete was considered as the baseline measurement as it was representative of the urban surface, hence it was deducted from other measurements to see how vegetated surfaces behaved in comparison to it.



Run 1 - 06 to 07 September 2016
Run 2 - 20 to 21 September 2016
Run 3 - 04 to 05 October 2016
Run 4 - 15 to 16 November 2016
Run 5 - 01 to 02 December 2016
Run 6 - 16 to 17 December 2016
Run 7 - 26 to 27 January 2017
Run 8 - 8 to 9 February 2017
Surface temperature (°C)
16:00
18:00
20:00
22:00
00:00
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
Time
Concrete area 1
Concrete area 2
Vegetation area 1
Vegetation area 2
Grass under tree
Exposed grass

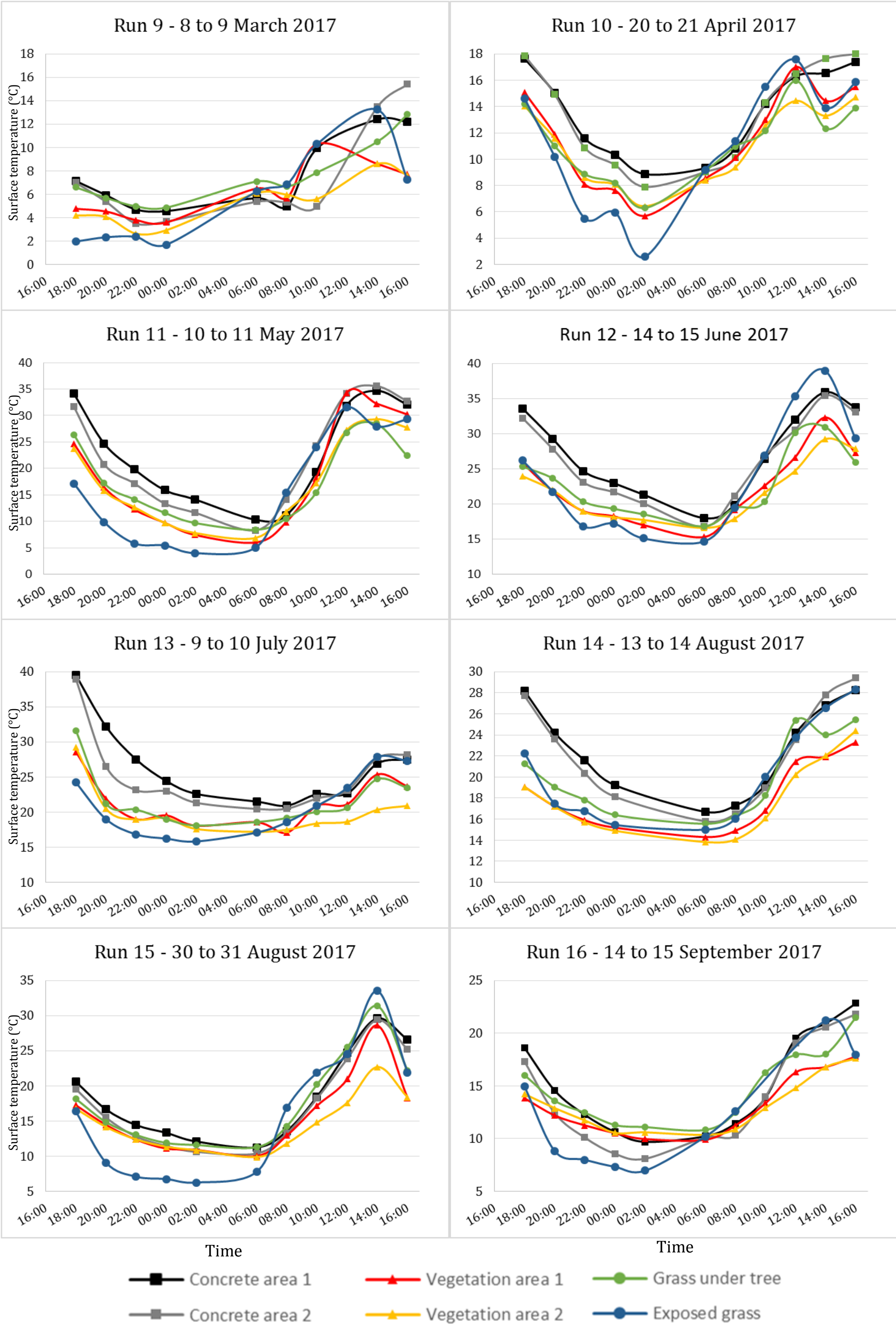
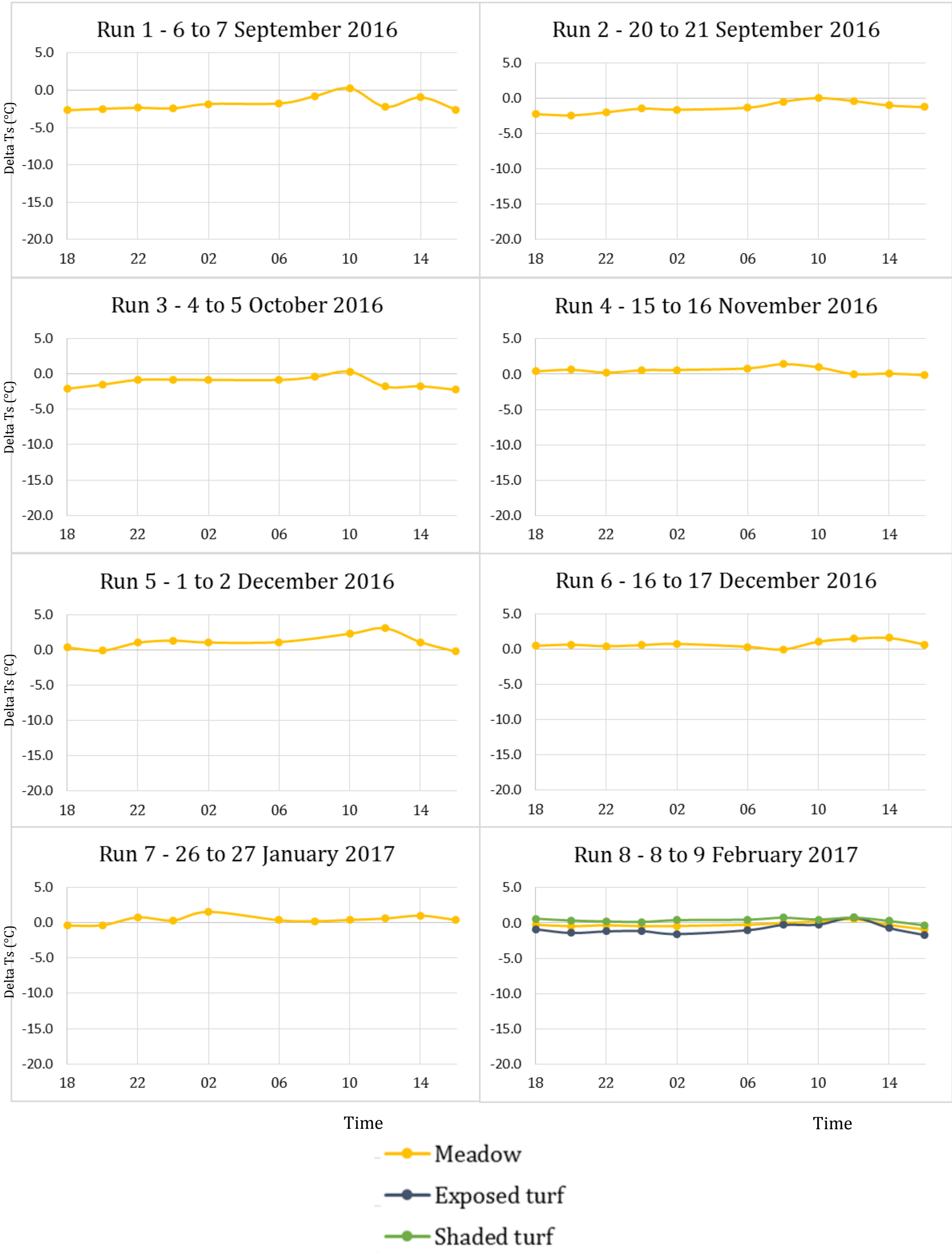


Figure 6.6: Surface temperature (°C) measurements of four different types of surfaces on the Grey to Green.


Run 1 - 6 to 7 September 2016
Run 2 - 20 to 21 September 2016
Run 3 - 4 to 5 October 2016
Run 4 - 15 to 16 November 2016
Run 5 - 1 to 2 December 2016
Run 6 - 16 to 17 December 2016
Run 7 - 26 to 27 January 2017
Run 8 - 8 to 9 February 2017
Delta Ts (°C)
5.0
0.0
-5.0
-10.0
-15.0
-20.0
18
22
02
06
10
14
Time
Meadow
Exposed turf
Shaded turf

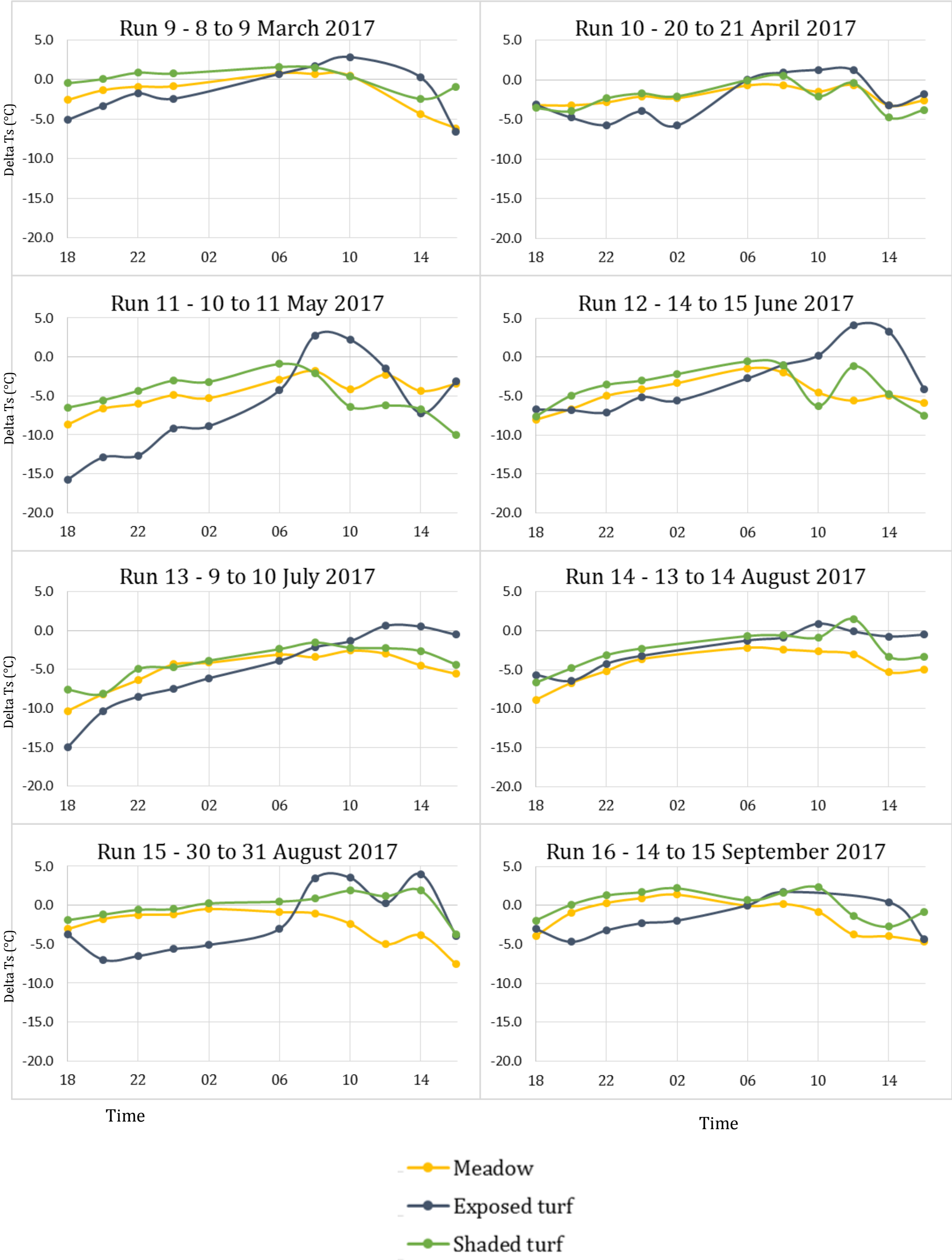


Figure 6.7: Surface temperature comparison of vegetated surfaces versus concrete ($\Delta T = T - T_{concrete}$). All representations have the same scale. Positive values indicate the concerned surface is warmer than concrete and negative values indicate it is cooler.

6.4.5 Error analysis

In order to assess the validity of the obtained results, it is necessary to consider the uncertainty within the measurements made (NIST, 2000). In the present case, three kinds of errors affect the value of the thermographic measurand (the quantity being measured): accuracy (systematic error), precision (random error) and environmental error (systematic or random error). It is understood that every effort was made to reduce human error (also named Gross Error) and that the procedure was made in accordance with the manufacturer's manual (FLIR, 2013). Environmental errors may be due to varying amount of solar radiation or rapidly changing conditions (such as the advent of a shower). When the conditions were very sunny, creating an artificial drift towards high thermal reading, then the measurand was shaded to allow dissipation of excess heat. The random component of environmental errors, such as unpredictable changes in weather conditions, were reduced, in the field, by minimising the time taken for each measurement and by the use of a calibration tape with fixed surface smoothness and emissivity. As a last resort, if measurements were anomalous due to improper shading or had extreme values unaligned with the general trend then they were discarded. This was the case with all the measurements at 12:00 on Run 9 (March).

The two most prominent sources of uncertainty left were hence accuracy and precision. The former refers to the distance between the measured value and the real value of the measurand and the latter to the distance between measurements themselves (Joint Committee for Guides in Metrology, 2008). The accuracy is given as a standard uncertainty by the manufacturer and is, according to Table 6.1, within ±2% of the measured value. It is assumed to be uniform across all temperatures, since no other information is given about it. The precision is given by the standard deviation (with Bessel's correction) between measurements of a same surface conditions divided by the square root of the number of measurements (Advanced Instructional Systems and University of North Carolina, 2011; Biau, 2011). To obtain the standard uncertainty, which is the combination of the accuracy and the precision then the Law of Propagation of Uncertainties must be used, it takes the form of the root sum square of the individual uncertainties.

$$Total\ Error = \sqrt{Accuracy^2 + Precision^2}$$

In order to obtain a gross estimate of the uncertainty, all measurements for each type of surface for either the day or the night of each run were considered at once. The process was as follows: the standard error for each surface type at each time point was calculated. The standard errors for all surface type, during either the day or the night, were averaged (Tatebe, 2005). These standard errors have a confidence level of 68% (since they are based on a single standard deviation). Thus to increase the confidence level in the estimated accuracy must be multiplied by a value corresponding to a confidence level of 95%. For this purpose, each standard error was multipled by a Z-score of 1.96 (value for alpha = 0.025 of a two-tailed test). The Z-score was chosen over the T-score as each individual measurements extracted from a single thermograms may be seen as the mean value of hunreds of pixels thus creating an original data set with thousands of values, in which case the Z-score is appropriate. Following suite, the choice was made to use the relative error, $\frac{Error}{Mean\ measured\ value}$, and expressed in percentage, which was easier to handle and similar to the manufacturer's reporting of accuracy. Hence, the standard error for the day and the night were divided by the average day or night temperature. Lastly, the Law of Propagation of Uncertainty was used to combine the accuracy and the standard error to create the Total Error. The accuracy was assumed to have a 95% confidence level. Figure 6.8 shows the Relative Total Error across the various runs as a percentage of the mean measured value in these data sets.

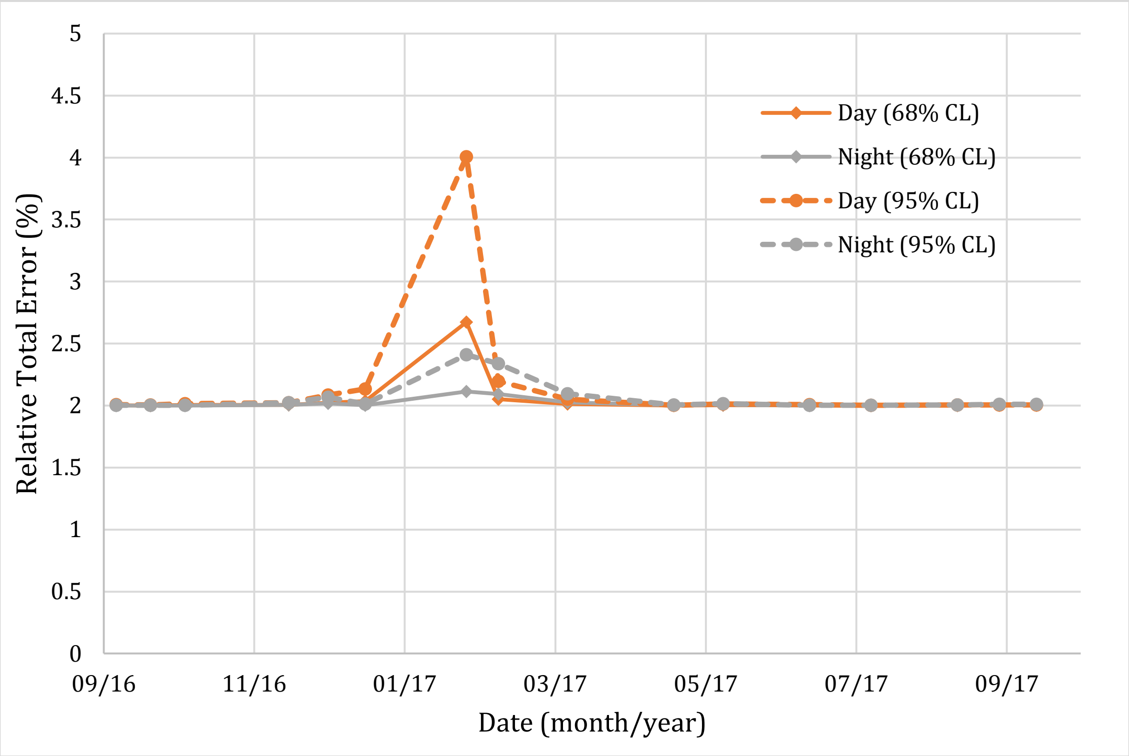


Figure 6.8: Relative Total Error expressed as a percentage of the actual values. The errors are reported for both 68% and 95% level of confidence. The error terms were averaged for all conditions but divided according to time of day: night (20:00 to 06:00) and daytime (18:00 and the next day's 08:00 to 16:00).

It may be observed that generally speaking, once systematic environmental errors were omitted, the Relative Total Error remained around 2 – 2.5% of the measurements. The most prominent driver of this error term is the accuracy of the camera (at 2% of the measured value). Otherwise, the precision remains mostly around 0.5% throughout the year.The exception to this the measurement during the middle of winter and during the day. This is due to the fact that the accuracy remained the same but more importantly the absolute precision (standard deviation), which was usually null to around ±0.5°C throughout the survey, represents a higher percentage of the measured value as measurements get closer to zero; hence it appears on Figure VI8 as an increase in Relative Total Error. This was particularly the case for Runs 7 and 8 (January and February respectively) where T_s was between +2 and -2°C, as shown in Figure VI6. At its worst, the Total Relative Error is still low at 4%. It is comforting to observe that, otherwise, there are no major differences between the nigth time and day time Total Errors. Night conditions tend to be more stable from a radiative standpoint with just purely LWR emission. The day time Total Relative Error being close to that of the night indicates that the procedure, and the use of Super 88 tape for homogeneous surface smoothness and emissivity, successfully accounted for uncertainty arising from field errors and that the omission of certain data points made the whole dataset coherent.

6.4.6 Thermal behaviour of the exposed turf

The exposed turf shows the greatest within day variation in all of the runs except in Run 8 where all surfaces' comparative values are close to zero throughout. Through the evening and night the turf is usually the coolest surface, regardless of the season. The difference from concrete is usually the biggest at 18:00, the maximum difference with the latter is -15.3°C reached during Run 11 (May). The specific time when the differences between the exposed turf and the concrete reverses seems to vary according to season, getting closer to summer seems to shift the timing towards later hours. For instance, during Run 13 (July), the temperature difference becomes positive only at 12:00 while during Run 16 (September) this point is reached at 06:00. When positive, the temperature difference is quite variable within and between runs; the maximum positive difference is 4.1°C reached during Run 12 (June). Both the original and the comparative data indicate that the exposed turf behaves like a countryside surface. Indeed, in the same radiative conditions it tends to visibly heat up more than concrete in the middle of the afternoon but is characterised by much lower nighttime temperatures. This level of variability is characteristic of countryside surfaces (Erell, Pearlmutter and Williamson, 2011).

This characteristic may stem from two possible factors. The first may have to do with the fact that turf is characterised by a limited root system and depth (Landschoot, 2017) which could prevent efficient overall evapotranspirative efficiency and hence local cooling. Additionally, the mowing regime of turf means that only a few centimetres of blades are present at any time. This strongly limits the potential of turf grass to shade the soil and hence may lead to higher surface temperatures. Another factor that would certainly contribute to the observed variability of temperature difference is thermal storage and inertia of concrete. Indeed, this type of material is known to have the ability to accept and store much more thermal energy which leads to higher late afternoon surface temperature whilst the smaller thermal storage within the turf would mean a decreasing temperature as radiative load decreases (Roth, 2013). Thermal inertia, defined as the slowness with which a body loses its heat to come to equilibrium with its surrounding, would make the concrete reduce its temperature slowly through the evening whereas the turf would lose it rather quickly. These factors explain both the sudden drop of the exposed turf's T_s right after dawn (shown in Figure VI6) and a relative flattening of the curve throughout the night while the temperature difference is greatest as soon the sun stops shining but is diminished as the night progresses (shown in Figure 6.7).

Conversely, for day time temperatures, the lack of transpirative cooling is an unlikely explanation as results presented by Peters, Hiller and McFadden (2011) showed cool turfgrass exhibited a higher transpiration behaviour than trees. However, there is a great reduction of evapotranspiration from around 12:00 to about 15:00. Janik *et al.* (2015) demonstrated that for four representative turf grass species, the evapotranspiration rate is divided by 2, 3 or is close to null during a few hours after mid-day (see Figure 5 in their paper). This would obviously reduce or halt phase-change heat transfer and lead to momentary temperature elevation. This fact sheds light on the dramatic increase in T_s of the exposed turf between the hours of 12:00 and 14:00, after which point it dips again (except in Run 14 where it continues increasing) potentially due to the continuation of evapotranspiration. In parallel to this fact, the specific heat capacity of concrete may lead to a reduced rate of temperature increase even though radiative load is still present. This could explain that comparatively speaking the turf appears hotter under similar conditions. In practice, it was observed that on all runs the turf was hotter around mid-day but by 14:00 its surface temperature was cooler again.

6.4.7 Thermal behaviour of the meadow

Runs 1, 2 and 3 (September to October 2016) show the meadow as being cooler than the concrete, commonly in the range of -3 to -1°C difference. Through the night and early morning, the temperature difference was around -2 to -1.5°C. At 10:00, the difference is null and after this point it stays within the same cooler range. Within these summer conditions, the meadow reduced surface temperatures. This effect may be due to a mixture of partial soil shading and available water for evapotranspiration. However, these measurements were made during the vegetation's first year of growth and hence surface cover was not extensive, additionally most taller growing species had not reached their optimal height, limiting the impact of the meadow on the soil's temperature.

Runs 4, 5, 6 and 7 (November to January) which occurred during calendar autumn and winter show the inverse dynamic to the three prior runs. There the meadow seems to be warmer, with a few exceptions, than the concrete. The maximum difference was registred at 12:00 on Run 5 with a positive 3°C. Otherwise, the meadow seems to commonly be within 0 and +1°C warmer during the morning and night hours. It is generally between closer to or above +1°C warmer in the afternoons. During this period, the meadow is on average 0.6°C warmer during the night (18:00 to 06:00) and 0.8°C during the day (8:00 to 16:00). While surprising, these results may indicate that plants that were still alive as well as soil microbiotic activity may have produced a small amount of heat that lead the surface temperature of the meadow to be slightly higher than that of concrete in winter conditions. This would be further supported by Run 7 where at its coldest the meadow's T_s is -2°C whereas the concrete's goes down to -4°C and by the fact that the meadow is rarely below the temperature of the concrete.

Amongst all the runs, Run 8 (February) is an exception. The meadow's surface temperature is very close to that of the concrete with values between 0 and 1°C. The values are negative except for the hours of 10, 12 and 14:00. This behaviour departs slightly from the other winter runs. This trend may be due to the plants having been cut back during the annual maintenance, which involves a single winter cutting, thinning down their biomass and potential heat generation as hypothesised above. Alternatively, it could also be purely the reflection of really cold conditions, the air temperature peaking at 18:00 with 3°C and staying around 0 and 1 °C during the night and 2°C from 12:00 to 16:00. Additionally, daily total irradiance measurement indicated maxima of 165.6 $W.m^{-2}$ and 83.9 $W.m^{-2}$ for the 8th and 9th of February 2017, which are indicative of very low incoming SWR. This factor may have influenced the fact that no surface heated or cooled down significantly compared to one another. Equally, Run 9 (May) differs from the following runs with the meadow's temperature being higher than the concrete's at 06, 08 and 10:00, by less than 1°C. It is possible that a mid-day warming is observed due to poor soil shading and hence a larger surface to receive solar radiation. Run 9 looks like a transition run, after which the meadow is consistently cooler than the concrete.

The trends of the runs 10 to 15 are similar. As the heart of the summer is approached, it seems the meadow's evening and night temperatures get further away from the concrete's. At its most pronounced, the difference between both surfaces is 10.3°C

(18:00, Run 13, July). Generally, the differences becomes less pronounced as the mornings unfold, presumably due to the concrete cooling as well, albeit more slowly due to its inherent thermal inertia referred to earlier. However, around sunrise (06:00 or 08:00), the minimum difference is reached, it ranges from -0.6°C in Run 12 (June) to -1.8°C in Run 11 (May). The only exception to this trend is that the minimum difference is reached at 02:00 during Run 15 (-0.5°C), the difference is nevertheless still -0.9°C at 06:00 of this same run. From this smallest difference between surfaces, the gap widens again as the morning ends and the afternoon starts. This is most probably due to the concrete heating up much more due to the lack of shading and its low albedo which is concomitent with the meadow shading the soil surface and providing cooling via evapotranspiration.

During these spring and summer months, it appears the density of plants has an effect on T_s. There was a difference in surface cover with Area 1 retaining open gaps throughout the growing seasons while Area 2 was densely covered in grasses and forbs. Generally speaking, there exists a slight difference between both meadow surfaces during the day, typically in the order of 1°C. When the sun's radiation is at its peak, during mid-day, there is a more pronounced difference between surfaces temperatures of the meadow. Runs 13 and 15 demonstrate best the large discrepancy that can exist in this regard. At 14:00, Area 2 was 5.1°C and 5.9°C, respectively, cooler than Area 1. While it may be observed that, generally speaking, Area 2 is cooler than Area 1, at these same time stamps the concrete in Area 2 was warmer by only 0.8°C on Run 13 and actually cooler by 0.2°C on Run 15. This differential cooling cannot be, hence, entirely attributed to microclimatic conditions. These results are coherent with experiments that measured shortwave radiation attenuation through forb canopies (Samaali *et al.*, 2007). In a similar vein, Sanusi *et al.* (2017) demonstrated that increasing the "Plant Area Index", which is the "estimate of the fraction of ground shaded by the vertical projection of tree crowns" (p 503) of a tree also increased microclimatic benefits. This link thus highlighted, it provides a valuable insight indicating a meadow's cooling effectiveness is maximised by increasing its density.

An exception to this summer trend of negative differences between meadow and concrete is Run 16 (September). It starts similarly to the previous set but past 22:00 and until 06:00 the difference is positive indicating that the concrete is cooler than the meadow. After sunrise, the surface then behaved as expected by being cooler than the concrete, as low as -5°C at 16:00. However, an interesting pattern may be observed here. During this run, the first recorded temperatures, at 16:00, were 18.0°C for concrete and 14.0°C for the meadow but by midnight these were 9.6°C and 10.6°C respectively with the meadow being slightly warmer than the concrete briefly prior and following this time stamp. In parallel, it is interesting to note that the switch of thermal behaviour of the meadow between Run 3 (October) and Run 4 (November) also happens around a threshold value of 10°C. Indeed, during Run 3 the nighttime T_s is stable around 12°C (below that of concrete), however during the next run (and other winter runs) where temperature are below 10°C (around 7.5°C throughout the night) then the meadow exhibit a higher surface temperature than concrete. Thus, Run 16 alongside Run 4 may be indicative of the existence of a threshold T_s value situated around 10°C below which the meadow starts behaving differently compared to the concrete, effectively conserving thermal energy.

6.4.8 Thermal behaviour of the shaded turf

In appearance, the treed surface seems to not have clear trends that emerges from either Figure 6.6 and 6.7. Its absolute minimum temperature is 1.2°C reached at 06:00 of Run 8 (February) and its absolute maximum is 31.6°C reached at 18:00 of Run 13 (July). Generally speaking however, it reaches its lowest temperature around 06:00 and its maximum temperature at either 12:00 or 14:00. From Figure 6.6, it is visible that the shaded turf shows the least amount of variation among the vegetated surfaces from the concrete's baseline, its range is typically confined to a difference of -5 to +2°C with the latter. It was at most 10°C cooler than concrete on Run 11 (May) at 16:00 and at most 2.3°C warmer during Run 16 (September) at 10:00.

While Run 8 (February) represents an exception in comparative terms, the area remained warmer than concrete except at 16:00. During Run 9 (March), the treed area was warmer than the concrete through most of the night but was cooler after 10:00. Run 10 to 14, however demonstrate similar trends. Throughout, the treed area remained cooler than concrete, except once at 12:00 during Run 14 (August). During this set of runs the temperature difference between the shaded turf and concrete was minimal at 08:00, usually close to null, and maximal at 16:00 and 18:00, i.e. in the late afternoon. In Run

15 (August), although the difference is negative during the night, it becomes positive at 06:00 and remains between +1 and +2°C until 16:00 where it drops back in the negative. Finally, and similarly to other surfaces, Run 16 (September) is different to most other runs in that the T_s of the shaded turf is higher than that of concrete during the night and remains so until 12:00, possibly due to a shading effect around mid-day allowing T_s to remain stable while the concrete's temperature increases.

The canopy of the trees on top of the shaded turf surface (as shown in Figure 6.2B) are aligned in a straight line, parallel to the axis of the walkway they are next to. Of similar age and shape, they have a canopy which starts at about two metres height and has a vase shape intertwined with each other. This particular spatial arrangement may lead to partially unrestricted absorption of diffuse and direct radiation; given Sheffield's latitude (53°23'N), the sun is more likely to be away from the zenith, meaning a large portion of SWR is not vertical and hence not intercepted by the canopy. This feature is particularly visible at 12:00 of Runs 12 (June) and 14 (August) where the radiation load increased suddenly and, being unobstructed, the surface temperature went up. However, outgoing LWR is reflected back onto the ground by the very existence of this continuous canopy, leading to an increase of T_s. This reheating phenomenon, added to a smaller thermal inertia, but balanced by evapotranspirative cooling may explain the fact that the shaded turf is generally closer to the concrete's temperature yet cooler during the hotter periods of the year.

There exists a fundamental methodology difference between our protocol and others' which also study T_s (Smith *et al.*, 2011 and Sanusi *et al.*, 2017, for example): the choice of days. Contrarily to most, climatic conditions without clouds (unobstructed SWR) and without wind (no convective heat exchange) were not sought. This method was rejected on the basis that Sheffield's climate pattern rarely includes these kind of days so measurement runs would be less numerous and less representative of an average day. This often meant that irradiance was not high thus reinforcing the observation that outside of a situation with intense direct SWR (rarer in Sheffield) trees have a more variable effect on T_s and that canopy configuration determines a tree's cooling efficiency on an 'average day'.

6.5 Discussion

6.5.1 Cooling efficiency: UHI

Figures 6.6 and 6.7 represent the results of a yearly survey of four surface types: concrete, meadow, exposed and shaded turf. Through twenty-four hour cycles, each surface type was monitored every two hours providing insights in both diurnal and nocturnal behaviours. While the exposed turf showed no particular seasonal variation, it demonstrated the greatest daily variation with lowest night time temperatures and mid-afternoon T_s which regularly were above that of concrete. In contrast, the shaded turf showed the least variability, seasonal and daily. Lastly, the meadow, the focus of this research, showed an intermediate daily variation with surface temperatures cooler than concrete in spring, summer and autumn. In winter, however, the behaviour changed and the meadow was quite consistently warmer than the concrete. It was clear that some form of threshold value existed, most probably situated around 10°C, beneath which the meadow had a warming effect rather than cooling.

These results would suggest that the premise that trees are better than other plants forms to combat negative effects of urbanization (Bowler *et al.*, 2010) is not verified in the present study. During the heart of the summer, the average T_s of the meadow was commonly cooler than the turf shaded by the tree, both during the day and the night. This contradicts the commonly held assumption that trees have a higher UHI combating potential than lower growing vegetation (Edmondson *et al.*, 2016; Salmond *et al.*, 2016). As highlighted earlier, this may be due to a differential interception of SWR. While the canopy of trees started only around two metres height, the meadow provided a canopy that started around one and a half to two metres and a vegetation layer which extended down to the ground. This layer might have provided a more effective attenuation blanket than trees. This is coherent with the cooling efficiency being linked to ground cover and plant density (Sanusi *et al.*, 2017). The meadow vegetation with lower percentage cover provided a lesser temperature reduction than the denser one; in the latter case, the soil was blanketed entirely in tall growing grass blades, stalks and leaves. This also indicates that the growth habit of tall blade-like plants (as opposed to the broad leaves of deciduous trees) is not necessarily detrimental to surface temperature reduction provided the density is high enough; a similar conclusion may be derived from Snir, Pearlmutter and Erell's (2016) research where the Kikuyu grass, if supplied with enough water for transpiration, provided a greater surface temperature reduction than lower growing succulent plants (rosette or rampant growth habits) in an arid climate.

Strictly speaking, this study found that in Sheffield (Cfb, temperate oceanic climate), meadow vegetation, trees and exposed turf all had some positive effects on the urban environment by notably reducing the night time surface temperature throughout most of the year thereby contributing to a reduction of the sUHI. This joins a number of studies (summarised in Kleerekoper, van Esch and Salcedo, 2012 and Bowler *et al.*, 2010 for example) which found a positive effect of vegetation on surface temperature. However, the exposed turf with its regular overheating beyond concrete's temperature during midday and early afternoon might further contribute to daytime sUHI while its low night time T_s indicates efficient emission of LWR. In this study, treed surfaces did not benefit as much of a temperature reduction as one may expect from previous studies (Edmondson *et al.*, 2016), probably due to their specific canopy structure. Their effect was most visible during the most intense radiative hours of summer. The meadow however has shown to provide a good balance of night and day time temperature reduction; for example during summer, the meadow was commonly around five degrees cooler than concrete and around ten degrees cooler during really hot periods. While these reductions are lower than those found by Armson, Stringer and Ennos (2012), it must be remembered that context is different, their study having been conducted in a park with a much larger water storage potential for evapotranspiration whereas the swale in which the meadow is installed is designed to evacuate water thus creating dryer conditions.

6.5.2 UHI and climate change prediction

In the North of the United Kingdom, climate change is predicted to make summers dryer and hotter while winter would be warmer and wetter (Jenkins *et al.*, 2010). Within this perspective, the Grey to Green seems fit to maintain liveable living conditions. Its SuDS element was designed to intake additional rainfall as exposed in Chapter 2. The choice of vegetation seems adequate since it withstood both drought and temporary high ground moisture, roughly a six-fold difference according to Figure VI3. This adequacy is corroborated by the general health of the vegetation throughout the observation period: it grew tall and dense and flowered abundantly; thus increasing confidence in the scheme's future hydrological performance. The UHI is expected to worsen with climate change, and particularly so in summer with less available water for evapotranspiration and higher air temperature (Kleerekoper, van Esch and Salcedo, 2012). From Figure 6.5, it can be seen that the two hottest days occurred on runs 12 and 13. Figure 6.7 demonstrates, that under such circumstances, the meadow performed slightly better than trees, by 1°C or so. Additionally, throughout the summer, the meadow had lower daily minimum temperatures. Taken together, these results grant confidence in the ability of the meadow-dominated vegetation to deliver its regulating ecosystem services in more extreme climatic scenarios.

6.5.3 Implication for thermal comfort

A major limitation of the present study is the fact that it was not undertaken at the same time as the questionnaire and thermal comfort study presented in Chapter 4. Part of the reason for this disjoint is that vegetation was still sparse and lower growing at the time of undertaking said study. As such, it was deemed that from a microclimatic standpoint the effect of the meadow would not be representative. As such, no direct comparison of data is possible. Incidentally, it may reinforce the conclusions of Chapter 4 in the sense that if the meadow had had a weaker effect on the comfort index then it made the psychological benefit of the green space that much more relevant. In any case, the findings presented in this chapter may still have implications for street thermal comfort as well. As exposed earlier, T_a was equivalent around the Grey to Green and in a more built-up area. However, it is likely that the vicinity with the scheme would improve thermal comfort. A person's heat stress may come from overhead downward solar radiation which would not be intercepted by the meadow. However, an equally important phenomenon is radiative heat transfer. A heated surface will transfer energy onto nearby bodies, such as a person. In this case, the meadow lower T_s would result in a reduction of such transfer. It is likely this would show as well in the Physiological Equivalent Temperature (PET) derivation. Indeed, outgoing LWR, reflected SWR and temperature of neighbouring surfaces are all components in the derivation of thermal comfort indices (Matzarakis, Rutz and Mayer, 2010).

In this regard, Armson, Stringer and Ennos (2012) found no significant effect of surface cover on mean radiant temperature, but they only considered low growing grasses or park turf. In contrast, Snir, Pearlmutter and Erell (2016) found that there indeed was a visible effect of grass cover on an Index of Thermal Stress. They found the latter to be tied to the proportion of vegetated surface, the higher the proportion the more benefit on thermal comfort. They do report that the reduction they measured would still put the subject in the “warm” category on a sunny day, however shifting them towards the lower end of this stress bracket. Directly relevant data, from a tall and dense herbaceous vegetation in a Northern city is not yet available so the comparison is limited. Given these conclusions, it may thus be expected that the meadow vegetation provides, at least, a weak thermal comfort service. It evidently cannot compare to the capacity of a tree canopy to block SWR from reaching the ground and therefore to lower the radiant temperature for pedestrians.

6.5.4 Winter results

While most research focus on the summer months, less is known on the effect of GI during winter and the inter-seasons. While a full comparison with turf surfaces (exposed and shaded) is not possible given the later additions of these conditions to the study, it may be said that the meadow exhibited a surprising behaviour by having a higher surface temperature than concrete. As the temperature difference was tenuous, in the order of a degree, it is unlikely that it would have a significant effect on pedestrians' thermal comfort during the winter period. These findings must be contextualised by the fact that the vegetation was not yet fully established and as such these dynamics might change in the future. However, if this phenomenon is the result of microbial activity and partial wind breaking then there are no reasons to believe this behaviour would disappear. This potential as a wind barrier (except if the dominant pattern is parallel to the linear swale) may provide more benefits than deciduous trees which would have shed their leaves at this period of the year. Additionally, some authors have reported that the warming caused by the UHI effect might be beneficial to cities during the cold season (Davies, Steadman and Oreszczyn, 2008). It is unclear whether the swale, even though continuous on several hundreds of metres, which occupies a small portion of the total width of the street could affect the micro-climate during winter. Indeed, it is often the case that there is a minimum size requirement, depending on specific urban context and latitude. In the case, of the provision of the Park Cool Island is uneven and usually linked to larger vegetated area in order to have an effect beyond its area (Bowler *et al.,* 2010; Erell, Pearlmutter and Williamson, 2011).

6.5.5 Drought tolerant meadow as an urban design tool

The premise of this study was to gauge the meadow's influence on micro-climate and it can be concluded that they appear useful all year round. This efficiency could easily be extended to green roofs. The latter are known to reduce summer surface and sometimes air temperatures (Butler and Orians, 2011; Susca, Gaffin and Dell'Osso, 2011). Given their efficiency at ground level, their implementation on green roofs might lead to further summer temperature reduction. Additionally, their covering property might provide better winter insulation than smaller growing plants and hence better energy efficiency to the building they sit on (Castleton *et al.*, 2010). Their capacity to be used in this context is further supported by the good health of the community within the rapidly draining and carbon-poor medium of the Grey to Green, a growing medium not dissimilar to those of green roofs.

In essence, the meadow of the Grey to Green derives its properties from a series of unique characteristics. A dense multi-layered arrangement ensures that a good portion, if not all, of the ground is covered (as seen on Figure 6.2A and 6.2C). The diversity of plants within the community ensures that different growth habit are present and hence multiple storeys are present within the meadow meaning the three dimensional space (particularly in its vertical component) is well occupied. Lastly, the inclusion of taller growing species means that the meadow space begins much higher than usual grassy vegetated areas. This combination of horizontal and vertical occupation of space seems to provide good SWR attenuation. This mirrors findings by Lundholm *et al.* (2010) where green roof efficiency was improved by a combination of plants with different growth habit. These authors also suggest that biodiversity itself seems to provide a synergy in the system and improve the overall health of the community as well as its ecosystem services; a phenomenon certainly applicable to the naturalistic meadow of the Grey to Green.. Individual species have been chosen for their capacity to tolerate, or even resist for others, water deficiency within the swale. This tolerance to drought ensures that when water becomes depleted, and subsequent evapotranspirative cooling decreases, the grasses and forbs would not die. Death of grasses nullifies T_s reduction (Snir, Pearlmutter and Erell, 2016) but if maintained alive the biomass may still provide shade on the soil, hence continuing a minimal climatic ecosystem service. These properties make this kind of meadow an effective and interesting tool to, at the very least, combat the UHI.

6.6 Conclusion regarding meadow vegetation

This chapter was dedicated to the study of one of the possible regulating services offered by vegetation: the regulation of microclimatic processes. The Urban Heat Island effect was introduced as it constitutes a significant issue in modern cities. The UHI is effectively the process by which the urban fabric overheats and stays warmer for a few hours after sunset. Vegetation, through shading and evapotranspiration, may locally offset this accumulation of heat and provide thermal respite to humans, slow the rate of formation of atmospheric pollutant and lead to decreased energy expenditures of buildings. Little was known of the effect of tall growing, dense and geometrically diverse urban meadow vegetation on this process. This study focused on the surface temperature component of the UHI. It notably found that the meadow vegetation had a significant impact on reducing the surface temperature which contributes to reducing, locally, the UHI. This proves that meadow vegetation does indeed deliver regulating services and that it benefits humans by increasing liveability.

Incidentally, our results confirmed that trees also offer surface temperature reduction benefits; however in Sheffield's Cfb climate it was observed that the Grey to Green's meadow was on average more efficient at doing so. Despite not being undertaken in parallel of the thermal comfort study (Chapter 4), the results presented here suggest that a fully mature meadow may reduce thermal stress for pedestrians standing next to it by reducing the reflected radiative heat. The meadow would not, however, provide overhead radiation attenuation like mature trees would. Finally, as the Grey to Green stands, it seems adequately fit to deliver regulating ecosystem services. Installed as a SuDS with drought tolerant flora, it may provide water retention and detention services. By its very presence, it is now also proven that it helps reducing the UHI and hence regulate the microclimate.

Chapter 7: Validating Envi-Met for use as a predictor of climatic benefits of meadow-dominated SuDS

7.1 Introduction

Tying in with the overarching themes of studying how meadow vegetation may deliver regulating services and, as part of the Grey to Green, how it may optimise the SuDS output of ecosystem services, this chapter aims at exploring the use of a microclimate simulation program, Envi-Met, as a predictive tool for the impact of this type of vegetation. The aim of this study is to verify whether Envi-Met can reliably predict the thermal dynamics of herbaceous vegetation which could then be used for local scale (street or block) prediction of the microclimatic benefits of SuDS or green area. Indeed, a planner's or landscape architect's toolkit would be greatly augmented if such a software could predict regulating services, and subsequent thermal comfort, from different vegetating scenarios. Informing design choices might allow professionals to create locally optimised SuDS schemes for example.

The previous chapter has given empirical proof that meadow vegetation reduces the surface temperature significantly and in doing so it contributes to the reduction of the Urban Heat Island effect. However, no significant differences in air temperatures were observed between the site and the reference urban location. Differences that were observed were attributed to configuration differences (openness of the street notably) rather than to the presence or absence of vegetation. The previous study was limited in that it did not include a systematic measurement of air temperature at different heights above and within the meadow which would have given a clearer picture of the thermal behaviour of the vegetation. On the other hand, a single point of measurement of the air temperature for the whole area may be considered as a limited indicator of the local effect of herbaceous vegetation given Sheffield is a particularly windy city which tends to equalise air temperatures.

It is therefore interesting to turn to modelling when considering potentially subtle or very localised changes in air or surface temperature. It also does not require extensive equipment. However, in order to use a model it must first be validated against real empirical data. This chapter thus constitute a first step towards the validation of a simulation software for use as a predictor of heat fluxes in and around meadow vegetation. This chapter is divided into two parts; the first was to gain a broader understanding of the functioning of Envi-Met and the manner it handles different kinds of vegetation. The second part focused its attention on herbaceous vegetation specifically and used surface temperature as its main variable of interest.

7.2 Background

Envi-Met is a Computational Fluid Dynamics model, meaning it is designed to handle numerical analysis of certain flow parameters and the energetic interaction between various types of surfaces. Its scope is to simulate the outdoor microclimate and must thus handle complex geometry arising from urban, landscape and vegetation morphologies. In addition, the materials used in said morphologies must be taken into account in order to accurately predict the energy exchanges between the atmosphere and surfaces. The sheer complexity of the urban microclimate that Envi-Met aims to predict has given rise to researchers (such as Samaali *et al.*, 2007 and Yang *et al.*, 2013) first needing to test the accuracy of the model before it could be used as a predictive or research tool.

The Envi-Met simulation module comprises a couple of sub-models (Maleki *et al.*, 2014). First and foremost, the core of it is the main 3D model (referred to as the model or simulation area henceforth). The user may build their urban environment within this model and set its dimensions in the three planes. At the top of the main 3D model, there exists a 1D atmospheric sub-model and the bottom there is an additional 3D soil model. The interaction of these three models will simulate the sources and sinks of temperature, the three dimensional movements of wind, the radiative balance, the interaction of the soil and the plants with the atmosphere etc.

The particularities of this model lie in the fact that the simulated environment is fairly customisable. The software offers the users the capacity to decide which material buildings are made from, what type of soil or ground surface is present; the model also provides an estimation of the 3D geometry of the trees used. As it is an on-going project, all the potential needs are not necessarily met but users also have access to databases to create their own surface or plants with their own custom properties. As it currently stands in its free version (Version 4.2.0), the model does not allow the user to dynamically include rainfall or water movement within the soil. This may be a limitation for SuDS modelling since SuDS are designed to manage water flows. However, obtaining a more 'static' view of the behaviour of the scheme might still be informative. As initial moisture levels may be adjusted, a scheme filled with water could thus be compared to a dry one to obtain an overview of its climatic benefits depending on its moisture content.

7.3 Literature Review

Previous work with Envi-Met has mostly focused on two aspects: validation and quantitative greening scenario simulations. The first aspect is validating the model by gauging how close it matches reality or theoretical behaviour. In this strand, Wania et al. (2012) tested the pollutant dispersion component. Using a simple crossroad of two street canyons, they varied the height to width ratio as well as the type of vegetation present in the canyons. While they did not compare simulation results to real-life measurements they judged the model to be accurately representing accumulation and dispersion of pollutants as a function of canyon properties and vegetation size and foliation. Similarly, Samaali *et al.* (2007) compared Envi-Met's handling of short-wave radiative transfer within the plant canopy to other confirmed model and experimental results. They concluded there was a good match between observed and simulated radiation balance between the canopy and the atmosphere.

The second type of studies are represented by the work of Perini and Magliocco (2014). By using three variables, air temperature at 1.6 metres, mean radiant temperature and the Predicted Mean Comfort (an index of human thermal comfort), they used a real-life base to model how increasing densities of vegetation on roofs and on the ground would impact the UHI. Comparison of simulation results indicated that vegetation on the buildings (green roofs) had a positive impact on the cooling load of the building but not much impact on street comfort. In contrast, street vegetation had the inverse effects. They also concluded that the effect of vegetation on decreasing UHI is more effective with higher temperatures and lower relative humidity in a Mediterranean context. Skelhorn, Lindley and Levermore (2014) performed a similar work for a suburban area of Manchester (Temperate Oceanic Climate) by looking at the relative differences associated with different greening scenarios and notably concluded that a 5% increase in mature trees could reduce summer surface temperatures by 1°.

Other studies have focused on other uses of the simulation software. For example, Taleghani *et al.* (2015) looked to predict, using ENVi met, how urban forms influence climatic variables and influences, in turn, thermal comfort measured with the Physiological Equivalent Temperature. To the best of our knowledge, a few things have not yet been tested within Envi-Met. Usually the tests made are at neighbourhood scale, Zölch *et al.*, (2016) used a 4000 m^2 and Skelhorn, Lindley and Levermore (2014) a 403200 m^2 area for example. It is thus unclear how vegetation would perform at smaller scales. The approach often chosen in these studies is to add increasing amounts of mixed vegetation (that includes grasses, hedges and trees). It is however unclear how these individual types of vegetation might perform. In the same vein, they also use different species within a single simulation and thus how the properties (Leaf Area Index, Albedo etc.) of individual species affect the output is also unknown. In summary, the majority of studies have attempted to validate specific areas of the model or used it to assess how a certain quantity or density of vegetation would affect urban scenarios. Therefore, there is a lack of clarity regarding the effect of different types and species of plants.

7.4 Overview of the method

Tests for this study were undertaken using Envi-Met 4.2.0, software functionality may evolve in the future with further releases from what is described here. In this version, Envi-Met has the following general process. One must first define the three dimensional model's size. In its free version, the model can have a maximum of 100*100 grids in the plane field and 40 grids in the vertical axis. It is, however, advised to build the actual model on a maximum of 90*90*30 grids or less in order to make space for nesting grids to be implemented. The latter are additional layers that are not counted towards the output but are useful tools to avoid boundary conditions. The higher the number of nesting grids, the more "distant" is the initial iteration of an equation to the model i.e the more distant to the area that will produce the output (Bruse, 2009). In this first step, the user is allowed to set the geographical coordinates and altitude of the model; information used to estimate solar irradiation for example.

Then one must create a three dimensional model within the “SPACES” module. If trying to recreate a real life scenario, it is easier to import a 2D raster file of a map or satellite image to effectively ‘draw’ on top of it. At this step, it is useful to also rotate the overall contours of the input file in order to have a maximum of straight lines; Envi-Met uses orthogonal grids and building might be ill represented if not straight. This can be achieved by rotation of the model and making note of the angle compared to the North. The two-dimensional ‘drawing’ can include such information as soil or surface type on the ground, building height and presence of vegetation on top of it. The choice of vegetation is still limited, though some 3D component exist for a few species of trees. Additional modifications may be done once the viewer switches to the 3D view such as modifying the material that the envelope of the building is made of. The last optional step to building the model is to place “Receptors”. They are points of interest the user must set and for which the software will provide numerical data and a specific output file.

Thirdly, the “ConfigWizard” module is used to set the date, the initial parameters of the actual simulation. In this section, even in the free version, some aspects may be manually forced, i.e. input parameters as opposed to having the simulation estimate these parameters at each major time step. Parameters related to solar irradiation, fixed cloud cover, air temperature, humidity, soil temperature and moisture as well as duration and finally management of the time steps may all be adjusted. The simulation can then be launched. On the author’s desktop computer, an hour in the simulation was roughly an hour in real life. Lastly, the results can be visualised using a built-in module, “LEONARDO”. The latter allows the user to produce heat maps or vector maps of the different variables at selectable heights.

7.5 General Validation phase

7.5.1 Objective

The objective of the validation phase was to crudely gauge the sensitivity and reliability of Envi-Met to simulate different simple landscape scenarios and have a sense of whether it would produce different results for these scenarios. The base scenario consisted of a building in a concrete environment with about a third of the area that could be implemented as a different land cover.

- Can Envi-Met accurately represent simple scenarios and are its results aligned with reality (general validation phase)?

7.5.2 Setting up the simulations

The model size was 60 x 60 x 30 grids and the grid size was 0.5 x 0.5 x 1 metres, the geographical coordinates were those of Sheffield. Four nesting grids were used. The model consisted of three thirds arranged along the North-South axis. The North third is occupied by a ten metres tall building surrounded by concrete. The central third is a concrete path. The variable area was a strip on the southern third of the model (see Figure 7.1). In order to increase the distance between the top of the building area and the top of the main 3D model, a telescoping factor of 10% starting after 10 metres height was used. This means that the z grid size increases by 10% compared to the previous one after ten grids, for u > 10, $dz_u = 1.1 \times dz_{u-1}$. There were five tested conditions which were: Asphalt, Grass dry, Grass wet, Trees dry, Trees wet.

Simulation were set to start at 05:00 (before sunset) and to stop at 22:00 with the production of an output every hour (see Table 7.1). The simulation day was chosen to be the 19/07/2016 which was one of the hottest day of the year in Sheffield, hence representing a hot summer day. In this regard, the lowest recorded temperature occurred at 4:00 and was 17.55°; the highest temperature was 30.81° and occurred at 16:00. The data was obtained from the weather station of the Hadfield rooftop (a building of the University of Sheffield). The humidity was manually set as Sheffield's daily humidity profile was quite different from the default one used by the software (see Figure 7.2). For the temperature, only the value and time of the maximum and minimum temperatures were set and the software linearly approximated the evolution of temperature between these extremums. The wind was set to flow from right to left (i.e. from the East) and have an initial speed of 0.492 $m.s^{-1}$ (see Table 7.1 for full list of initial parameters).

Initial soil temperature and humidity parameters were also changed. In the configuration file, the percentage that may be input is not total soil moisture but rather a percentage of what the authors call "Usable Field Capacity" which is equal to Field Capacity minus Permanent Wilting Point. It was chosen to halve the default values for a dry scenario and set a high water content for the case of wet soils. These choices were motivated by the fact that SuDS, with large drainage area but high drainage or conveyance capacity, may be temporarily close to field capacity and then remain dry for lengthy periods of time in the absence of rainfall. All initial temperature of the soil were set to 308 K (34.85°C) instead of the default 0°C. In the dry configurations, the soil's humidity was set as follows: upper layer, 25%; other layers at 30%. For the wet configurations, the soil's humidity was set to 80% for the three layers and 90% for "base rock". It is unclear if in the case of concrete, adjusting initial soil parameters made a change but for the sake of homogeneity, the soil temperature was set to 308K (34.85°C).

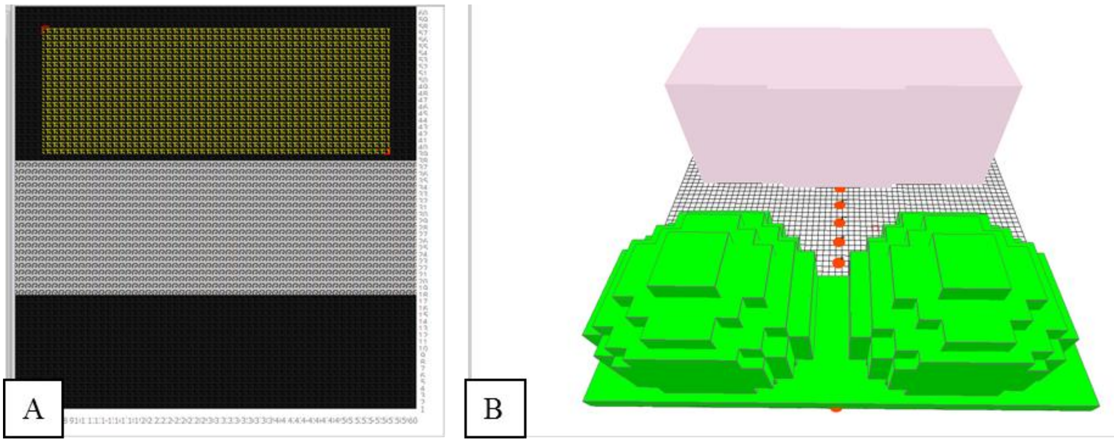


Figure 7.1: Configuration of the General Validation phase simulations.
A) The yellowed area on a black background indicates the position of the building (10 metres tall) that is present in all simulations. The grey area has been set to "Concrete Grey Pavement" to represent a footpath at the bottom of the building. The black area represents black tarmac, (set to "Asphalt Road" in the software), this is the variable part in each set-up.
B) The 3D representation of the Trees configuration where the Asphalt road was replaced with a strip of turf and two mature trees (Platanus, 10 metres high, 11 metres crown width) on top. The red dots represent receptors that may be placed by the user. Only the one in the middle of the variable area and the one in the middle of the sidewalk were used.

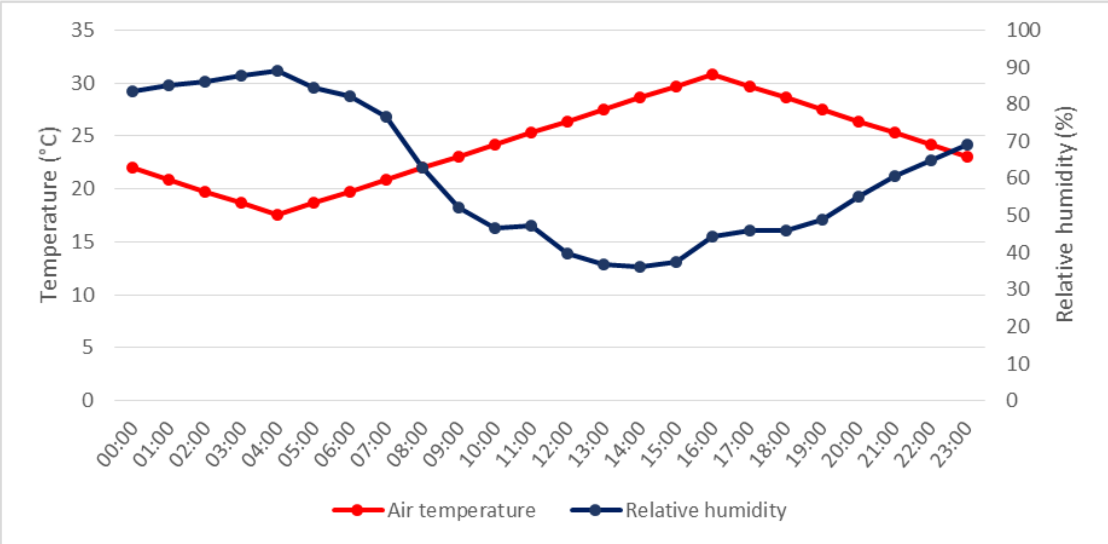
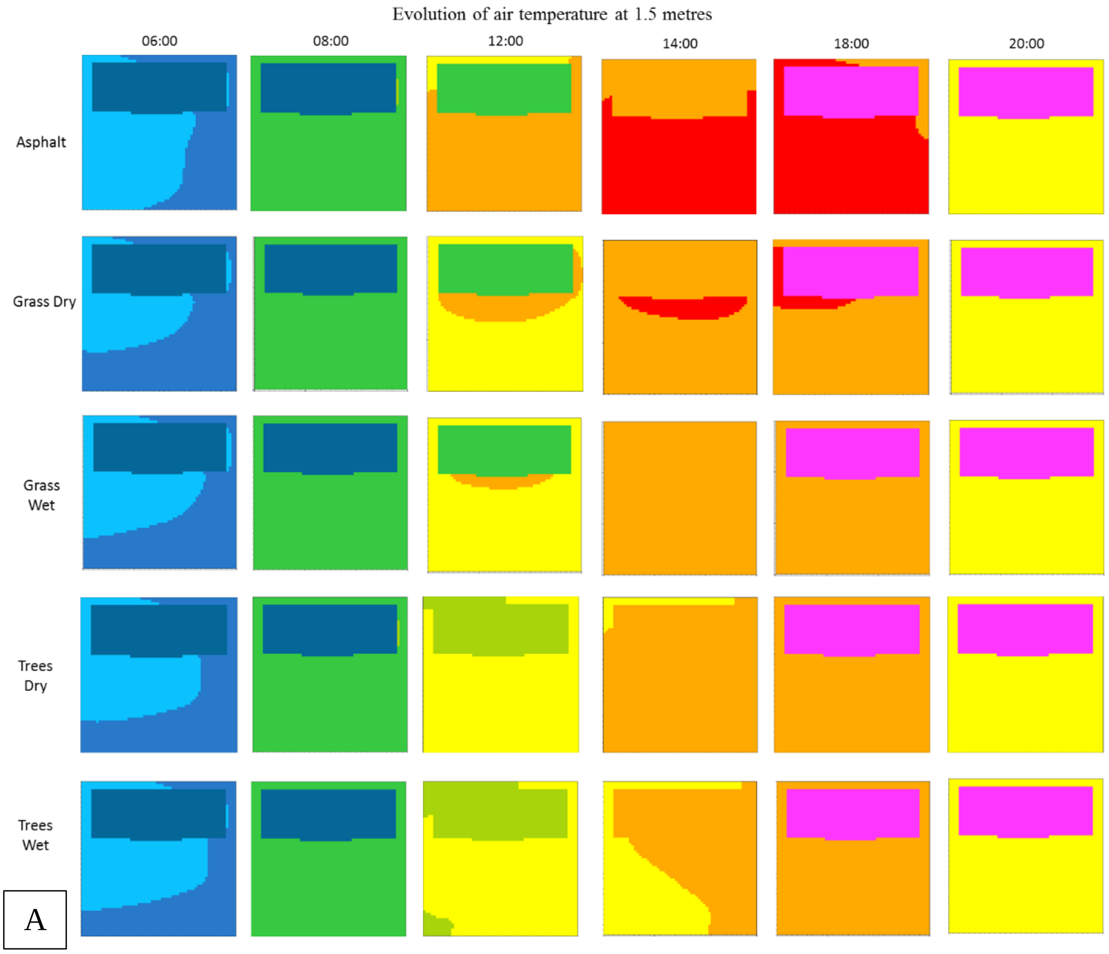


Figure 7.2: Air temperature and humidity profiles that were used for all the simulations mentioned in this chapter.

Table 7.1: list of initial parameters used for all the simulation mentioned in this chapter	
Date	19.07.2016
Beginning	05:00
Run time	17 hours
Output frequency	Every hour
Initial wind speed	0.492 m/s
Wind direction	90°
Roughness	0.01 *
Specific humidity at model top	7 *
Soil moisture	Variable, mentioned in the text
* refers to initial parameters that were left at their default values.	

7.5.3 Results from the General Validation Phase

Figures 7.3 and 7.4 contain some the exported maps from the LEONARDO module that allows the user to visualise the simulation results using heat maps and adjustable colour scales. The two key variables of interest are air temperature at 1.5 metres, which is roughly representative of the temperature felt at the centre of gravity (1.1 metres) of a human, which is the standard measurement height in outdoor comfort studies (Johansson *et al.*, 2014). The second variable is surface temperature which was the central variable in earlier chapters. The temperature ranges were chosen to encompass the highest and lowest temperatures while remaining small enough to gauge differences across surfaces. The temperatures range in Figures 7.3 and 7.4 are different, a key is provided at the bottom of each figure.



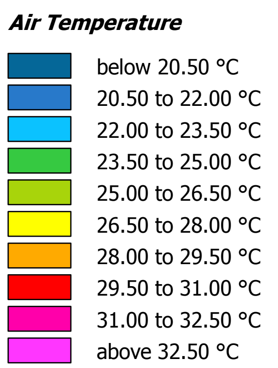
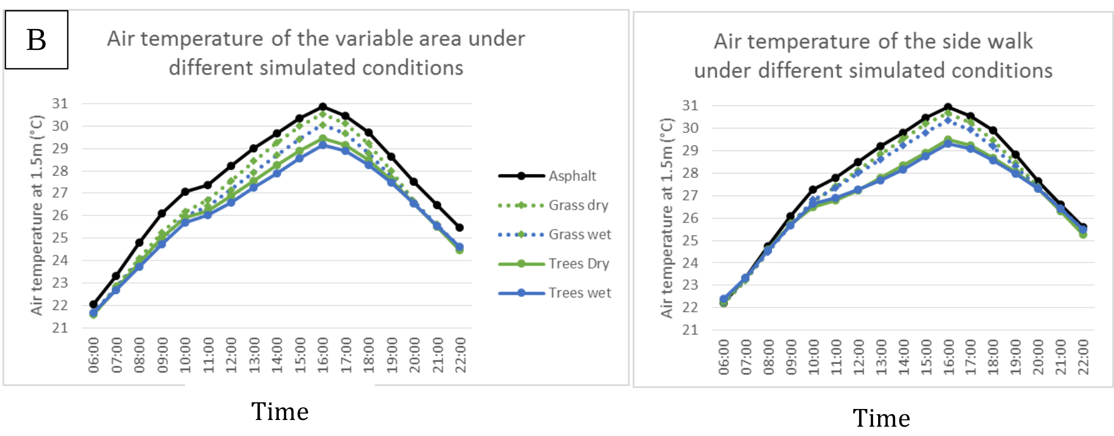
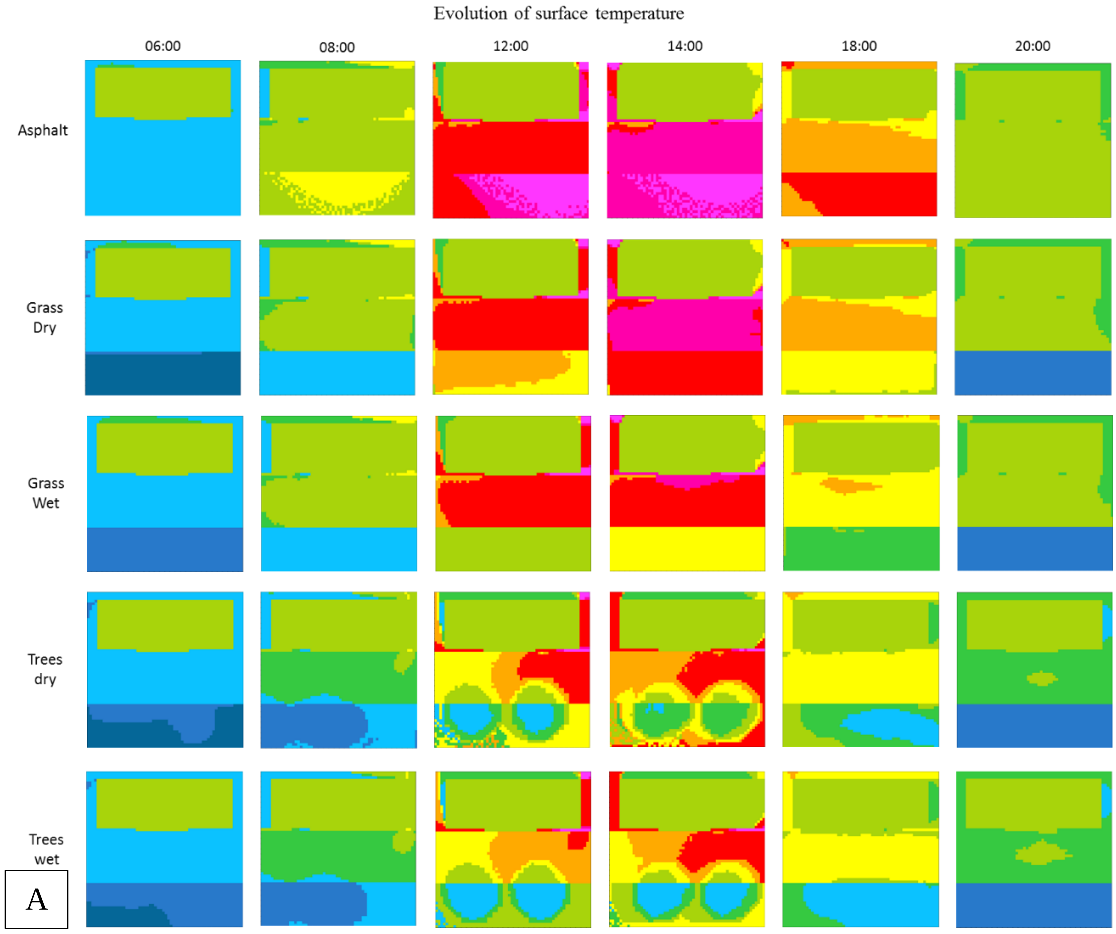


Figure 7.3: Results for air temperature of the General Validation phase
A) Air temperature at 1.5 metres (around human centre of gravity) during selected hours over all conditions. These heat maps were exported from the module LEONARDO. North is at the top of the page
B) Air temperature at two selected receptors. The first is in the bottom zone (variable area), the second on the sidewalk.





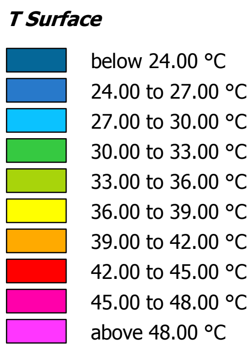
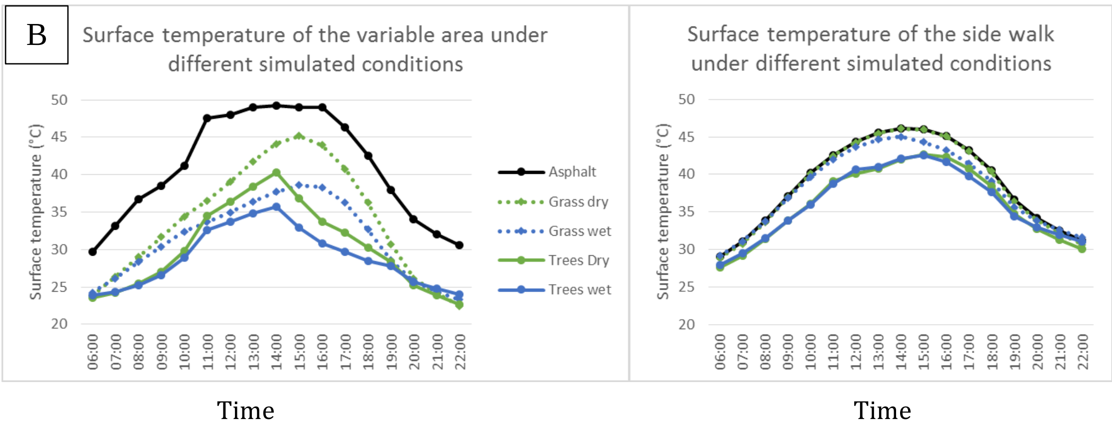


Figure 7.4: Results for surface temperature of the General Validation phase.
A) Surface temperature at selected hours of the day. These heat maps were exported from the module LEONARDO. North is pointing up.
B) Surface temperature at two selected receptors. The first is in the bottom zone (variable area), the second on the sidewalk.



In Figure 7.3, from the heat maps for air temperature, it is clear that there is not much noticeable difference in the morning. At the hours of 06:00 and 08:00, the heat maps are similar with only slight variation of the [22°, 23.5°] zone on the western side at 6 am. These differences might be due to different wind patterns, notably in the case of the treed simulations where there would be less convective heat transfer. During the hours of 12:00 and 14:00, there exists a clear trend of decreasing air temperatures as more plants are added. In both moisture instances Trees + grass is cooler than Grass, which is itself cooler than Concrete only. Additionally, wet configurations are understandably cooler due to evapotranspirative processes. At 18:00, only the concrete scenario is remarkably hotter, with the Grass Dry scenario having a small patch of higher temperature away from the patch of vegetation. The rest are within the same temperature range of [28°, 29.5°]. At 20:00, however, all scenarios result in the same air temperature ranges. In this set of simulations, it is visible that adding vegetation has an impact and that higher growing vegetation (trees) will have more impact than a low growing one on air temperature, during the afternoon notably.

In Figure 7.4, the heat maps represent the distribution of surface temperature. Here again, there exist noticeable difference between vegetated areas and different moisture levels. The temperature categories had to be wider here due to the concrete scenario heating up considerably. In all scenarios, increasing vegetation complexity (Trees versus grass) lowers surface temperature not only on their physical location but seems to have an impact on the simulated environment. Additionally, moisture level (dry versus wet) also reduces surface temperature. Remarkably, the crown of the trees are visible through their ‘shadow’ on the ground, which is translated by lower surface temperatures visible at 12:00 and 14:00. In these four results, it can be seen that the western part of the sidewalk is cooler than the eastern part, this is likely to be the combined effect of shading and evapotranspirative cooling.

7.5.4 Discussion of the results of the General Validation Phase

The first thing to note is that these simulations all had identical initial conditions, forced overall humidity and air temperature conditions. Hence, the only variable factor was what stood upon the lower area (Asphalt, Grass or Trees) and the initial moisture levels, hence any difference in results may be attributable to them. In order to assess the validity of produced results, a comparison may be drawn from an empirical study undertaken in the nearby city of Manchester. Armson, Stringer and Ennos, (2012) performed (independently from the present study) summer measurements of air and surface temperature over "amenity grass" and concrete with or without tree shading. This study was chosen given that the parameters were the same and the geographical location is similar. The authors studied the evolution of air and surface temperature of a concrete path within a park and surrounded or not by trees. While our simulations are set in a more urban environment with its building and surrounding concrete, the bottom two-third may be compared since the situation comprises either grass or trees and grass which is next to a concrete footpath. While they did not report soil moisture, they gave the following qualitative indication: "Grass plots never showed any sign of water stress, despite not receiving any irrigation" (p246). We believe this situation would fall between our Dry and Wet scenarios and is hence comparable.

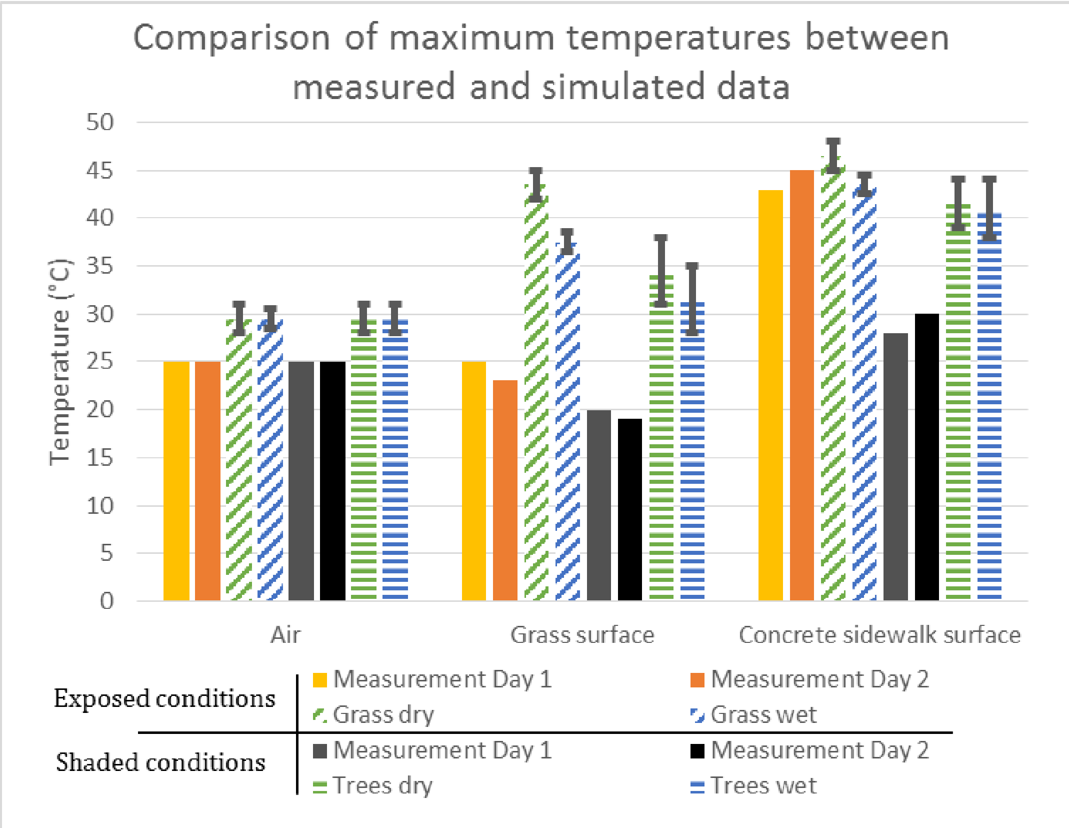


Figure 7.5: Comparison of modelled and measured maximum air and surface temperatures. Filled histograms represent measured data taken from Armson, Stringer and Ennos (2012) in either unshaded or shaded conditions over two different days. Patterned histograms represent the average maximum temperatures obtained from the various simulations and at various points within the model area. The error bars on the latter histograms represent the full width of the range.

As Figure 7.5 shows, average maximum air temperatures does not seem affected by exposure or surface type in the simulation. They are however about 4°C higher than their measured counterparts in the park. This is probably due to the Park Cool Island effect whereby large amount of vegetation brings temperature down compared to its urban neighbouring environment (Erell, Pearlmutter and Williamson, 2011). However, given crude assumptions done in this simulation and given the difference in context, this difference still seems reasonable.

For maximum surface temperatures of concrete, in exposed conditions it seems the model is in good agreement with the observations. In shaded conditions however, it seems that the model predicts the surface temperature to be at least 10°C lower than observed. It must be noted however that the small difference in between the two simulated results are in line with Skelhorn, Lindley and Levermore’s (2014) who found an overall average reduction of 1°C of surface temperatures with a 5% increase in mature deciduous trees. Similarly, using another climatic model Hall, Handley and Ennos (2012) demonstrated a reduction of 0.5 to 2.3°C of maximum surface temperatures thanks to trees. The large difference found with the empirical data shown in Figure 7.I5, could be due to improper short wave radiation attenuation through the canopy or an oasis effect measured in the real case scenario.

The surface temperature of grass, however, does not match up in any instances, with the simulation vastly overestimating the measured values. The maximum temperatures recorded in Armson, Stringer and Ennos (2012) are between 23° and 25° in exposed conditions and between 19° and 20° in shaded conditions. In comparison, in this simulation Envi-Met gives a range between 36° and 45° in exposed conditions and a range of 28° to 38° in shaded conditions. There are two factors that may influence these results. The first may be due to the fact that the measurements were done in the middle of a park and therefore would have benefited from a local cooling effect through advection for example. In retrospect, the initial conditions of soil temperature may have been too high (around 34°C), therefore influencing surface temperature. Another interpretation is that Envi-Met wrongly simulates grass patches and vastly overestimates their surface temperatures.

Not shown in Figure 7.5 is the absolute maximum temperature for the black asphalt road in the Asphalt simulation. In this scenario, these surface temperatures reached around 50° at 12:00 and 52° at 14:00. These high values are supported by a comparison with the measured surface temperatures of a rooftop sealed with black asphalt in Poitiers (France) (*Cool roofs in Europe: Initiatives and Examples*, 2010), which is also within a temperate oceanic climate. The daily summer variation, shown in Figure 7.3 of this document, indicates frequent maximum temperatures of 60° to 70° during summer. Hence, Envi-Met's prediction of asphalt's surface temperature could be considered qualitatively reliable.

In consequence, air temperatures around a human's centre of gravity, concrete and asphalt surface temperatures seem to have been predicted somewhat adequately by the simulation. However, more preoccupying for the modelling of SuDS systems, there exists too big of a disparity for the surface temperature of grass that necessitated further testing. Thus, at this phase Envi-Met, while being able to produce qualitatively different and credible outputs even in simple scenarios, is not validated for use of herbaceous SuDS.

7.6 Herbaceous Vegetation Validation phase

It is already known Envi-Met does not allow to dynamically add rainfall into its simulation runs but it does not preclude its capacity to simulate herbaceous SuDS with varying levels of initial moisture levels. Once familiarity of its functioning was acquired through the General Validation phase, this study intended to gain insight into the models' handling of herbaceous vegetation. The main axis that was pursued in this regard was how surface temperature, and other related variables, was affected if the following were changed.

- Overall climate
- Moisture levels
- Types of grass cover

7.6.1 Methods

Similarly to the last part, the methodology consisted on running simulations and compare them to real measurements to assess the credibility of Envi-Met's output. In this section, two scenarios will be examined. The first will compare published data from the Negev Desert (Israel) and the second will compare our data from the field study to Envi-Met's results. Israel's scenario was chosen because it represents a hot arid climate which strongly contrasts with the humid temperate climate Sheffield experiences. These two extreme climates should give an idea of Envi-Met's handling of different climate.

Two very different moisture levels were used in each climatic scenario. Envi-Met allows the user to manually input initial moisture percentage in the set-up phase. Counter-intuitively, the model does not ask the user for Volumetric Water Content but rather a percentage of the "Usable Field Capacity", which is defined as: Field Capacity – Permanent Wilting Point. This concept is more often referred to as the Available Water Content. It seems the model cannot handle, or at least does not allow the user to set, moisture levels beyond the fixed Field Capacity of a type of soil nor can it be changed to below the Permanent Wilting Point. In this study, 10% and 80% of Usable Field Capacity were chosen to represent respectively dry conditions and a moist environment. Within the two climatic scenarios, dry conditions would arise following the absence of rainfalls or watering in Israel. More moist conditions would happen on the day and the following rainfall in Sheffield or watering in Israel. Here again, the values are extreme to highlight how Envi-Met handles differences in soil moisture.

The last axis of research is how different grasses are handled by the model. Within Envi-Met V4.2.0, “simple plants” are still treated as 2D objects, unlike trees which have been converted to 3D objects to take into account their canopy structure. These simple plants differ by Leaf Area Density (LAD) which is defined as the “one sided portion of leaf surface within a volume of air”, its dimensions are $m^2.m^{-3}$ (Bruse, 2013). It allows the model to know the surface of interaction with the wind (technically the upper part of the leaves) and which surface will transform sensible into latent heat via transpiration through the stomata under the leaves. The LAD creates a variety of surface on which the simulation of a complex radiative balance (absorption, transmittance) as well as heat fluxes through each layer of the canopy is possible (Samaali *et al.*, 2007). The model actually creates ten LAD values per plant (Bruse, 2009). It treats the LAD as a Leaf Area Index within a volume and so over ten equidistant portion of the grass’ stem. It is a sort of 2.5D plant where its third dimension is estimated by ten different Leaf Area Index over a certain volume. Additionally, these simple plants also differ by their height, short wave albedo, root depth and Root Area Density, which is a similar idea to the LAD. For the purpose of this validation study, two plants were used that differ only by their Leaf Area Density and their root properties (Root Area Density and depth). Standard “Grass” was used as it is the default simple plant available and Soya was used for its similar height and for the fact that its top-most LAD was much higher than the grasses. Hence, Soya was thought of as a much more covering plant, perhaps more representative of denser meadow-like vegetation. Information about the plants are summarised in Table 7.I2.

Table 7.2: Basic information concerning the two plants used in these simulations taken from the plant database of Envi-Met

Name (Envi-Met code)	Grass (XX)	Soya (SO)
Albedo	0.2	0.2
Plant height	0.63 m	0.63 m
Root zone depth	0.5 m	1.2 m
Leaf Area Density	0.3 $m^2.m^{-3}$ at all points	1.58, 0.82, 0.38, 0.29, 0.27, 0.29, 0.33, 0.4, 0.52, 0.74 $m^2.m^{-3}$
Root Area Density	0.1 $m^2.m^{-3}$ and 0 for the last point	0, 0.9, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.76, 0 $m^2.m^{-3}$

7.6.2 General set-up

Both climatic and moisture scenarios used the same basic input file. As shown in Figure 7.I6, it consists of two lanes of grasses running parallel to the North-South Axis. The whole area has been set to the default loamy soil. Three receptors were placed in each vegetated area. Other characteristics of the model are presented their respective scenario set-up.

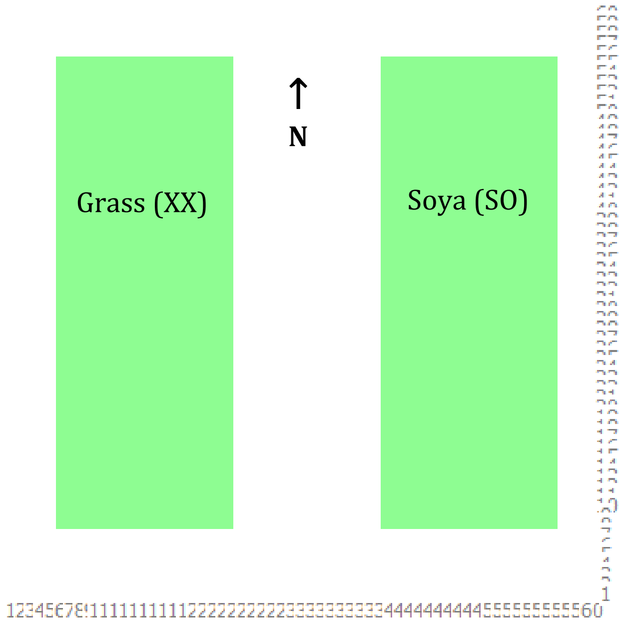


Figure 7.6: The simple input area used for all the following simulations.

7.6.3 Scenario testing

7.6.3.1 Scenario 1: Negev Desert in Israel

The simulation which represented Israel (Hot Arid Steppes Climate, BSh) was set up as indicated in Table 7.3. The date was made to coincide with one of the days for which Snir, Pearlmutter and Erell (2016) measured the surface temperature underneath their vegetated plots. The original article provided few details of the climatic parameters, except for the conditions at 14:00 which served as a basis for the estimation of the rest of the day. Solar radiation was adjusted in order to match that reported by the authors. Relative humidity was left relatively low as the experiments were originally made in an arid climate.

Table 7.3: Set-up and initial parameters of the Israel scenarios	
Size of the model	60 x 60 x 30 grids
Number of nesting grid	6
Grid size	2 metres
Vertical grids	Telescoping of 10% after 2 metres
Model coordinates	30.8 N; 34.78 E
Day of the simulation	12/06/2013
Start time of the simulation	01:00
Duration of the simulation	19 hours
Output interval	60 minutes
Roughness length	0.01 (Default)
Adjustment to solar radiation	0.94 of theoretical maximum
Cloud cover	None
Temperature	Min at 06:00 of 15° and max at 14:00 of 36.9°C
Relative humidity	Min at 14:00 of 10% and max at 06:00 of 30%
Initial wind speed	1 $m.s^{-1}$
Wind direction	315° from North
Initial soil temperature	26.85°C in all 3 layers
Initial Usable Field Capacity	Dry: 10% Wet: 80%

7.6.3.2 Results and Discussion of the Israel scenario

Within the simulated results, a clear pattern seems to emerge. In both moisture instances, the soya plants seems to drive the soil to have a lower surface temperature. This is most probably the doing of direct short-wave attenuation through the denser canopy. As could be expected in such a hot climate, the presence of a larger quantity of water in the soil has driven surface temperature down for both plant types thanks transpiration from plants and evaporation from the soil. In Figure 7.7, all the simulated plant types and soil conditions really detach themselves clearly in a manner that would be expected which is indicative of appropriate handling of these dynamics by the software.

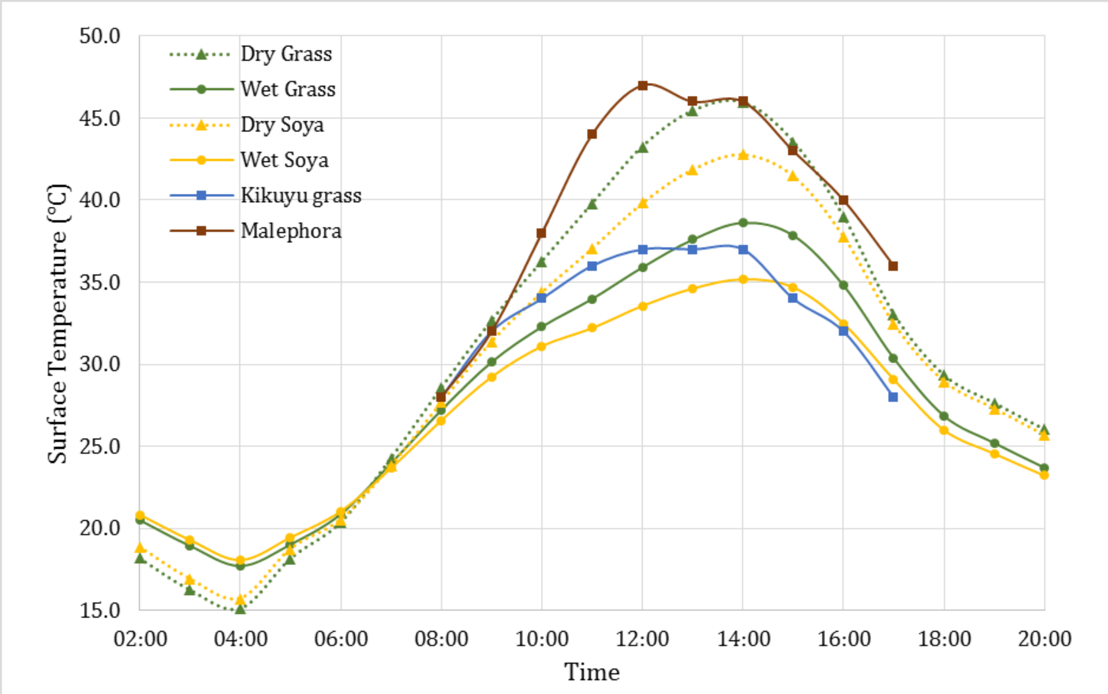


Figure 7.7: Comparison of simulated data with published data from Snir, Pearlmutter and Erell (2016) for the hot and arid climate. Simulated data includes surface temperature underneath the generic grass and the soya plants in two moisture levels. The Kikuyu grass (*Pennisetum clandestinum*) and *Malephora crocea* points were approximated from figures of the article and are shown for illustrative purposes and convenience of comparison.

Comparison with measurements made in-situ is rather positive given the crude assumptions made on weather parameters and the lack of knowledge about the physical characteristics of the plants used by the authors. The simulated Wet Grass follows most closely Kikuyu grass with an average difference between respective surface temperatures of 1.9°C. This makes the most sense given that both are grasses in the true sense with blade like leaves and the measurements were made under an irrigation regime which would allow plants to transpire. However, images provided by the original authors seem to indicate a denser growth habit than is assumed in the model with the Grass' LAD of 0.3 $m^2.m^{-3}$. This might explain why the Wet Grass' temperature remains higher until the end of the afternoon. Despite this, the difference is not big, with about a 1.6°C difference between maximal surface temperatures. Contrarily to what was suggested by the results of the previous section, Envi-Met does not completely over-estimate soil surface temperature under a grass cover.

Measurement made under the *Malephora crocea* plants behave quite differently. As suggested by Figure 7.7, they follow more closely the pattern made by the evolution of Dry Grass surface temperature. The average difference between both of 1.6°C is actually smaller than the difference between Wet Grass and the Kikuyu grass. The apparent contradiction of the irrigated *Malephora* matching closely the Dry Grass' evolution may be resolved with a double explanation. Firstly, the growth habit of *Malephora* is that of a small leaf horizontal creeper, this means that the canopy layer is thinner, usually a single layer which height is comprised between 1 and 2 decimetres (Solomon, 2014), than it might be within a grass and therefore lead to minimal shortwave attenuation. Secondly, *Malephora* is adapted to arid climate (it is a succulent) and as such its transpiration and water loss rate has evolved to be much lower during the day. Indeed, the original article reports that *Malephora* had the lowest water loss per day, losing 1.6 mm/day which was 4.5 times smaller than the Kikuyu grass (6.1 mm/day). This means that it does not behave like a grass, it also uses CAM photosynthesis to limit all form of transpiration during the day, it hence provides limited to no evapotranspiration benefits during the day unlike what is assumed with the plant in the model; hence why it seems to behave just like a grass in hydric stress. Even the comparison between *Malephora* and the hottest simulated grass condition is in agreement with Yang *et al.* (2013) in their observation that Envi-Met seems to under-estimate the surface temperature. Their research having been done in a tropical environment (hot and humid climate), which are usually closer to the equator, it is possible that this similar trend may result from Envi-Met's correct handling of similar incoming radiation load and subsequent heat fluxes. The first conclusion that may be drawn here is that even without a proper knowledge of the original conditions and plant characteristics, Envi-Met is capable of producing results which are credible (within a degree and a half) in arid conditions.

Incidentally, this demonstrates that the model may be used to approximate CAM plants even though it does not natively account for their specific photosynthetic strategy. Envi-Met deals with plant respiration using a modified version of the A-gs equation for stomatal conductance (Bruse, 2004). Briefly, this equation links stomatal conductance to photosynthetic rate, itself linked to two key parameters: H_2O use and CO_2 assimilation; the two key molecules to produce sugars in the presence of transformed solar energy. This equation is optimised for the C3 and C4 photosynthetic strategies which comprises most grasses and forbs. CAM photosynthesis, however, uses a different pathways that involves storing partial products made from the transformation of solar energy during the day and doing the part of the Calvin cycle which involves water at night. This allows CAM plants to only open stomata, which leads to water evaporation, at night when temperatures are lower. Hence, a bypass in the model to make CAM look-alike plants is to hydraulically stress C3/C4 plants which would then exhibit much lower daytime evapotranspiration rate, as illustrated in Figure 7.7 above with the Dry Grass. This, of course would, just like observed above, be at the expense of some cooling via phase-change heat transfer. Hence, this opens up the possibility to use Envi-Mets to notably simulate members of the *Crassulaceae* family, of which *Sedums* are a popular green roof choice.

7.6.3.3 Scenario 2: Sheffield City Centre

Given that a full study of the Grey to Green had already been undertaken, the data could be used to simulate the same patches of plants under a Temperate Oceanic climate (Cfb). One of the summer rounds of measurements was selected from the pool of available sets gathered for the previous chapter. Table 7.4 gives a breakdown of the model characteristics and initial conditions. Contrarily to the other scenario, a full (static) cloud cover had to be used in order for the modelled global radiation to match the observed one in addition to a percentage adjustment to the total radiation.

Table 7.4: Set-up and initial parameters of the Sheffield scenarios	
Size of the model	60 x 60 x 30 grids
Number of nesting grid	6
Grid size	2 metres
Vertical grids	Telescoping of 10% after 2 metres
Model coordinates	53.38 N; -1.46 E
Day of the simulation	10/07/2017
Start time of the simulation	01:00
Duration of the simulation	16 hours
Output interval	60 minutes
Roughness length	0.01 (Default)
Adjustment to solar radiation	0.94 of theoretical maximum
Cloud cover	8 octas in low cloud cover
Initial temperature	16.5°C
Initial relative humidity	64.7%
Initial wind speed	0.4 $m.s^{-1}$
Wind direction	262.5° from North
Initial soil temperature	293 K in all 3 layers
Initial usable field capacity	Dry: 10% Wet: 80%

7.6.3.4 Surface Temperature results of the Sheffield Scenario

Firstly, the simulation acted in a way that is similar to the previous one in that it showed a surface temperature difference between the two moisture conditions with the Dry plants creating higher surface temperatures than the Wet ones (shown in Figure 7.8). It was also expected that the difference between them would be more tenuous given a reduced solar radiation load. Indeed, in these sets of simulations the sky was fully obstructed with clouds, as is often the case in Sheffield (!!). Hence, the amount of radiation reaching the ground was low (in the order of 250 $W.m^{-2}$ during the afternoon both in the simulation and in real-life). The background air temperature was also correspondingly lower. It is encouraging to observe that in this context, maximum simulated surface temperatures are between 14°C and 22°C much lower than in the Israel scenario. This indicates good handling of vastly different climates as expressed by differences in geographical coordinates, solar radiation, initial soil temperature and air temperature.

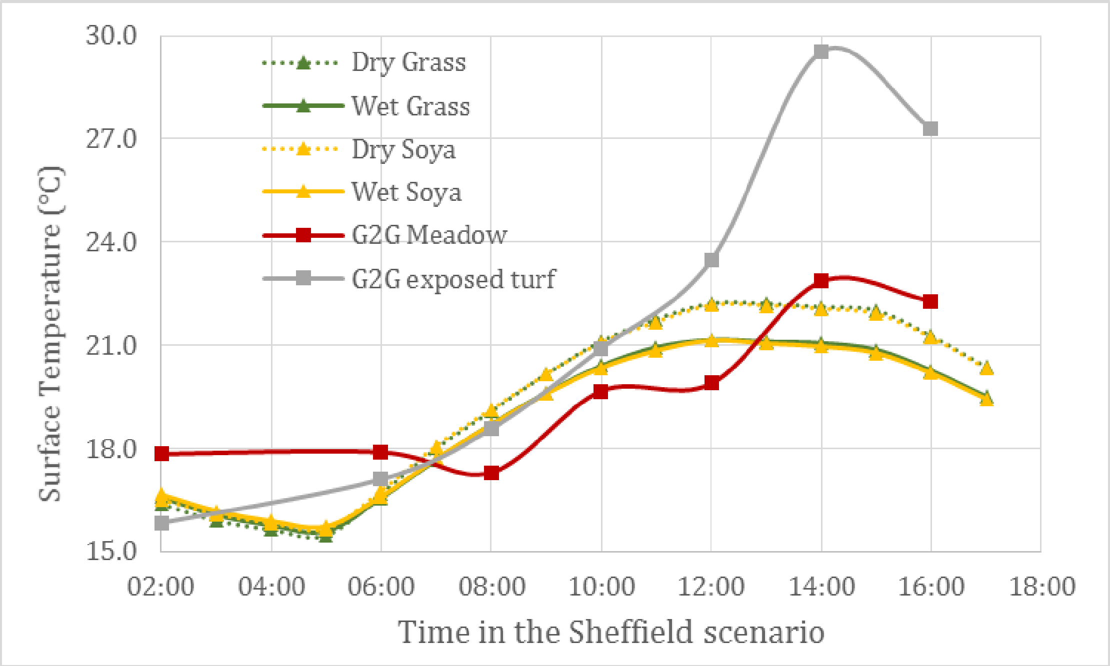


Figure 7.8: Surface temperatures of the measured and the simulated data in the Sheffield scenario.

The average difference between the meadow measurements and the simulated results is relatively small, ranging from 1.39°C for both Wet scenarios to 1.40°C for the Dry Soya and 1.42°C for the Dry Grass. It can be concluded that, as is, the model reproduces relatively well the evolution of surface temperature underneath the meadow. It must however be noted that the meadow vegetation was situated in an urban context, as such its temperature is expected to be higher than in the simplified model used for the simulations. The UHI notably increases night time air temperatures and surrounding concrete and other impervious surfaces may have contributed to a higher observed temperature. Additionally, it is visible that the initial simulated surface conditions (at 02:00) are lower than the meadow, this may be due to an improper input of initial soil temperature that could be corrected in further iterations. The surge of surface temperature at 14:00 and 16:00 in the meadow could have its explanation in momentary opening of the cloud cover that characterised that day, and hence more intense shortwave radiation.

Various other explanations including advection of hot air or progressive release of anthropogenic heat could have affected the overall heat balance.

While the exposed turf seems reasonably modelled up to noon, the measurements show a vast increase in temperature that is not reflected in the Grass simulation. This difference may be due to the fact that the turf was cut very low, in the order of a couple centimetres and has smaller root systems, in the order of 5 to 15 centimetres (Landschoot, 2017). This may lead to limited shading of the surface to short-wave radiation as well as limited evapotranspiration, two factors that lead to rapid increase of surface temperature (Erell, Pearlmutter and Williamson, 2011). Like exposed in Chapter 6, the turf acts like a rural surface with rapid progression of its temperature during the daytime and rapid cooling at night. This dynamic has not been represented by either of the plant and moisture level choices made in these simulations. It is however entirely possible that by setting a grass type with shorter stem and low LAD, a similar result may be obtained.

7.6.3.5 Soil temperature results of the Sheffield Scenario

Regarding soil temperature, it must be noted that the Grey to Green's 20 cm depth values were closer to values for the simulated 15 cm depth than to the simulated 25 cm depth by an average of 0.09°C, hence why 15 cm depth are shown below in Figure 7.9. 15 cm depth curves are much flatter than their 5 cm depth counterparts. This is an expected behaviour whereby lower depth show less daily temperature variation as corroborated by Yang's *et al.* (2013) findings. In the Dry scenario, the average difference between the measured 20 cm depth and the simulated -15 cm depth was 0.5°C. In the Wet scenario, values were even closer with an average 0.35°C difference. In this sense, it seems that initial parameters for that soil depth and its evolution match closely those observed on the Grey to Green. Furthermore, albeit small, there seems to be differences in the evolution of soil temperature in function of soil moisture at this depth as the Dry conditions seem to have created higher temperatures both at night and during the day than the Wet; this feature may be explained by lower moisture available for phase-change heat transfer.

Figure 7.9, shows different dynamics between measured and simulated values of soil temperature that does not give the same level confidence in the model as previous outputs did. It does show temperature differences between the simulated Dry and Wet conditions notably during the night and after 12:00, but these differences are small (<1°C). The major discrepancies, however, happen between the measured data and the simulated one. During the night, it seems the model under-estimated the soil's temperature by up to 1.7°C at 06:00. All of the curves overlap between 10:00 and 12:00 after which point the model seems to slightly over-estimate the soil's temperature. These differences are likely to have arisen, at least partly, due to an estimation error when inputting initial soil temperatures or differences in thermal inertia between the Grey to Green's substrate and the chosen "Loamy Soil" within the simulated area. It must be recognised, *in fine*, that the scale of error is relatively small (about a degree and a half) and that given the approximations made by the author, Envi-Met still got close matches with reality.

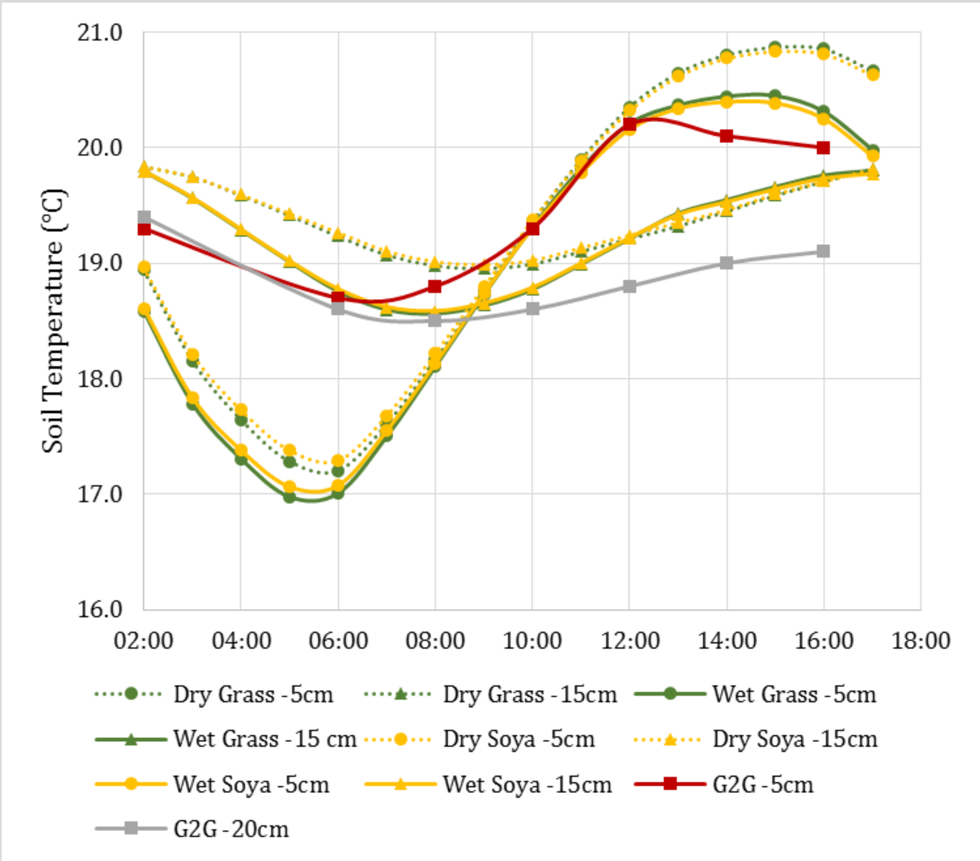


Figure 7.9: Soil temperatures at two different depths. Envi-Met does not provide an output for 20 cm depth so the closest options were chosen (15 cm depth).

7.6.3.6 Volumetric Water Content results of the Sheffield Scenario

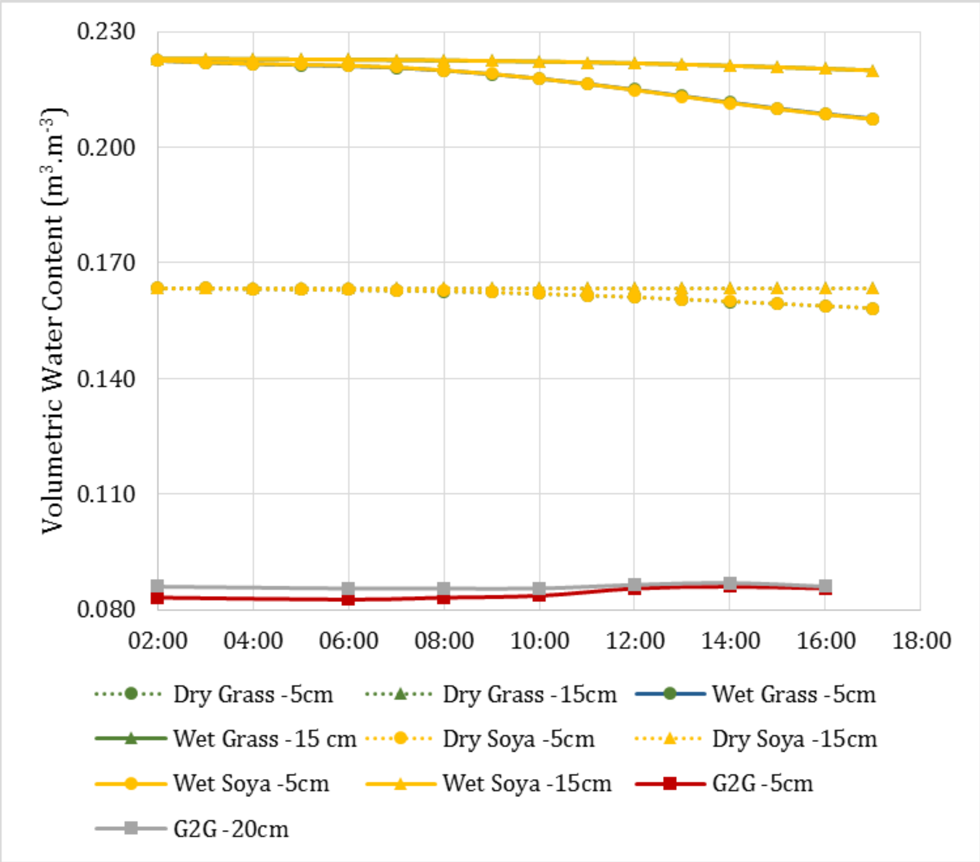


Figure 7.10: Volumetric Water Content at two different depths for two different moisture content scenarios and measured data on the Grey to Green.

The Volumetric Water Content (VWC) graph (Figure 7.10) shows similar dynamics for both plant types in both moisture conditions. In the Wet scenarios (top curves), moisture at 15 cm depth is rather stable throughout the modelled day. Moisture content at 5 cm depth, however, decreases throughout the simulated day, going from around 0.222 m^3.m^{-3} at 02:00 to about 0.207 m^3.m^{-3} at 17:00. This is most likely the result of moisture being used by plant to perform evapotranspiration. In the Dry Scenarios (initial parameter: 10% of Available Water Content), the difference between the two depths is not as marked, with an average decrease of 0.005 m^3.m^{-3}. This is comprehensible given that the intake rate of water in the soil requires larger pressures as the VWC gets closer to the wilting point.

The empirical data shows a VWC around 0.086 m^3.m^{-3} for the Grey to Green's substrate. This number is low but as seen in Figure VI2 of Chapter 6, this is not the minimum value for this growing medium. It seems its Permanent Wilting Point is quite low (around 0.050 $m^3.m^{-3}$) due to large particle size in the matrix. This result suggest that the plants were in a state of hydric stress when the surface temperature measurements were made. Hence, in this case as well, it is an issue with having chosen the wrong soil for the modelling. In effect, in the database it can be read that the Permanent Wilting Point is 0.155 $m^3.m^{-3}$ and its Field Capacity is 0.240 $m^3.m^{-3}$.

7.6.3.7 Discussion of the results of the Sheffield Scenario

It must first be noted that even with crude assumptions made, Envi-met showed it could produce an output that was quantitatively different across two vastly different climates (BSh and Cfd). Surface temperatures in the arid climate were up to 24°C higher than their counterpart in the temperate oceanic climate. Further comparison between various variables in the Sheffield scenario showed reasonable simulation results. While the differences in surface temperature between the simulated plants and the meadow planted areas were minimal, the turf's behaviour of very high afternoon temperatures was not replicated. Soil temperature did not provide such a clear cut and neither did Volumetric Water Content. However, in both instances the Dry and Wet scenarios followed expected patterns and absolute values different from the measured ones may stem from a wrong choice in soil which has different heat capacity and hydrological property.

Building a model that is closer to reality would be a first step towards improving Envi-Met's output. For instance, the model described plants through a set of parameters related to their radiative behaviour (albedo, emissivity etc.) and pseudo-3D geometry (height, LAD etc.) and only few species are currently available within the database (Bruse, 2009). Hence, field studies would be required to obtain the average set of parameters per species which would enable users to precisely represent the kind of plants found on herbaceous SuDS. However, these values would only be representative of single plant species. SuDS are usually planted with diverse forms of plant life, but the model does not take into account communities, just single species (Samaali *et al.*, 2007). Hence, another area of research is opened to obtain these same properties careful weighed in function of the prominence and average values of each species within a plant community. This would give designers the ability to control more precisely how their communities would impact local climatic parameters. Additionally, as was previously detailed, it looks possible, with some tweaking, to model daytime effect of CAM plants which are not natively modelled by Envi-Met.

The second important dimension to this work would be to create bespoke soils within the soil database that would match the hydrological and heat flux and storage properties of those in use for SuDS. It must be noted that these properties might only be relevant for the first few years of a SuDS. Indeed, as suggested by the work of De-Ville *et al.* (2017) on ageing green roofs, some of these more artificial soils tend to change properties, even over five years. While longer time comparisons would be needed to get a clear understanding of the evolving properties of artificial soils, it must be taken into account that growing medium used in SuDS is bound to change. For example, In Zölch *et al.* (2016) climate change scenarios are simulated fifty years in the future with a mix of green façades, green roofs and street trees. It cannot be assumed that the soil properties (let alone plant communities) will have stayed the same in this time span. Correcting for these factors would lead to improved simulation of future climatic scenarios.

Lastly, in order to prove that Envi-Met is capable to reproduce precisely SuDS (non-hydrological) dynamics, future work will have to involve careful and iterative calibration. In this matter, Skelhorn et al. (2014) reported going through multiple rounds of refinement of their model area, configuration and initial parameters in order to improve the R^2 values of their correlation between measured and modelled variables. A similar work would need to be undertaken in order to be able to precisely simulate existing SuDS and reliably make inferences when attempting to discuss various greening scenarios.

7.7 Conclusion

Little work has been reported in the literature on the appropriateness of Envi-Met, a CFD simulation software more traditionally used for atmospheric modelling in urban environments, to be used as a tool to model SuDS or meadow vegetation. Research on green roofs or green façades has usually assumed that the models were appropriate and applied different greening scenarios. This study reports on early validation work on the simulated behaviour of grassy vegetation within Envi-Met. Under crude assumptions and approximate initial conditions, the results showed strong positive signs of the model’s ability to replicate real-life dynamics, usually in the order of a degree Celsius or two. It was found that some of the assumptions had most probably impeded on obtaining good results, notably in terms of Volumetric Water Content and initial soil temperature. As such, this should encourage further work that would more systematically study Envi-Met's behaviour with regards to the evolution soil moisture, soil temperature and surface temperature as a function of soil and plant characteristics and initial parameters. It is also evident that the comprehensive determination of existing substrates and growing media's physical properties is necessary. Similarly, non-agricultural grassy plants in use in SuDS, such as Sedum on green roofs or meadow communities in bioswales, will need to be studied in order to feed their respective properties in the model. Only then will researchers and planners be able to know the level of reliability that Envi-Met holds with regards to simulating herbaceous dominated SuDS.

Chapter 8: Research highlights and perspectives

8.1 Research summaries

This body of work sought to study how urban meadow vegetation, through the provision of regulating and cultural ecosystem services, could improve urban liveability. Liveability was mostly treated from three angles: satisfaction with the sensory environment and the potential well-being it brings, thermal comfort in both its physical and psychological components and the improvement of the urban microclimate. In Chapter 2, the study site, the Grey to Green was introduced. Installed in Sheffield city centre within a low-medium density area, it is a linear greenway which served the purposes of bringing greenery in an otherwise built-up environment and to manage stormwater. To do so, the scheme notably relied on a meadow-dominated vegetation that is characterised by a high species and geometric diversity and by a lengthy flowering period. In order to increase environmental sustainability, the plants were chosen to be perennial and maintenance limited to a single winter cutting.

In Chapter 3, we first looked at the provision of cultural ecosystem services which may occur directly when an individual is in proximity with the green space. Two axes were followed: appreciation of the vegetation and perception of the streetscape. Users' views were gathered using a street questionnaire. Despite uncertainty regarding the acceptability of such unusual planting within a business and commercial district, results showed that it was accepted. The scheme notably scored highly in its aesthetic and naturalness components; it was also found highly fitting for its urban context. Its presence also improved greatly perceptual qualities of the street. While scores for safety-related aspects were modestly positive, improvements to the aesthetic experience of the street was high. A highly positive affect resulting from the retrofitting of the scheme was also noted. This chapter highlighted the capacity for meadow vegetation to be a sustainable urban ecosystem and have its users' adhesion. Cultural ecosystem services delivery was thus established.

In Chapter 4, the notion that urban meadows may deliver cultural ecosystem services was extended through the lens of thermal comfort. The objectives, here, were the establishment of a local thermal sensation scale, the investigation of potential influences of physiological acclimatisation and the potential benefit of the presence of greenery. Both climatic measurements and *in-situ* questionnaires were used. Deriving the Physiological Equivalent Temperature (PET), the chosen thermal comfort index, proved aberrant with the usual, linear, methods even though the results had the same statistical power than studies with bigger sample sizes and larger sensation scales. An alternative method, called the Averages of Thermal Sensation Interval (ATSI) method, was used to obtain a neutral comfort range for summer in Sheffield: 14.4 to 23°C of the PET. This is wider than the Central European Sensitivity scale and as such a new scale, more appropriate for northern Cfb climates, was proposed. Even this extended scale could not predict more than 60 to 70% of the comfort levels reported. The evolution of the PET of the month prior to the study was used to find evidence of long term (over weeks) and short term (over days) acclimatisation. The latter shone light on the high tolerance of respondents and the shift towards "Warm" responses to the Actual Sensation Votes (ASV). The remainder of the unexplained variations was theorised to be due to two perceptual qualities of the place of study: naturalness and aesthetic experience. Positively correlated to the ASV, it was suggested that they mediated thermal comfort by an increase of the positive affect. It was thus postulated that satisfaction derived from sensory and emotional experience of the Grey to Green lead respondents to have an increased thermal tolerance. This chapter thus proposed to extend the delivery of cultural ecosystem services of meadow-dominated vegetation to psychological benefits that increase tolerance to thermal discomfort.

After having positively correlated the psychological benefits derived from the proximity with the meadow-dominated scheme with thermal comfort, Chapter 5 sought to further investigate the existence and relationship between psychological factors and thermal comfort. The objective this chapter was to gain insight into the interaction of landscape appreciation, thermal comfort and thermal preference. The technique chosen was photo-elicitation using images with increasingly complex urban vegetated spaces and a series of weather descriptors; these options were based on the Grey to Green's linear greenway. A novel approach to describing a person's long-term thermal experience was tried. It was assumed that people's expectations and preferences were shaped by the place they had spent most of their time in their lives or in recent years. This place could then be ascribed a Koppen-Geiger code and thus constitute the Climate of Reference of a person. Using these digitally manipulated images with weather scenarios in an online questionnaire, it was determined that respondents preferred the most geometrically complex style of planting (with grasses, shrubs and trees) in an urban context. While fulfilling human preference for landscape complexity, it offered little extent and visibility which departed from other studies. Contrary to other studies, it was found that naturalness was not connected to landscape preference. Results confirmed the existence of schemata related to wind and solar radiation, even when the actual environmental stimulation was absent. Thermal expectation was connected to thermal preference and to landscape preference. However, thermal and landscape preference were not linked. The photo-elicitation to explore engrained thermal schemata and the use of the Climate of Reference as a surrogate for long-term experience proved to be useful tools in investigating psychological factors of thermal comfort. This reinforces the connections revealed in Chapters 4 of a person's transaction with a landscape and psychological adaptation to a thermal environment. In turn, this emphasizes the importance of cultural ecosystem services that urban meadows can deliver.

Moving towards regulating ecosystem services, Chapter 6 focused on the accumulation of heat in urban surfaces which contribute to a process called the Urban Heat Island (UHI) effect which has adverse health and environmental effects. The objective of this chapter was to compare the thermal behaviour of different types of surfaces: meadow vegetation, tree vegetation, turf and bare concrete. This study investigated the thermal behaviour of different surfaces around the Grey to Green scheme over 24-hours cycles throughout a whole year. Results indicated that the exposed turf behaved like an agricultural, or countryside, surface in that it showed greatest variability; it even was occasionally warmer than concrete. On the other hand, turf shaded by trees had the least temperature variations and the meadow was situated in between. The data showed that, in this particular context, the UHI was best combated not by trees, as frequently assumed in the literature, but by the Grey to Green's meadow vegetation. It was postulated the latter did so by providing a dense, overlaid, canopy that remained limited in height. As such, it is postulated that the meadow attenuated well shortwave radiation during the day time and yet let outgoing longwave radiation escape without reflecting it back the way trees do. A discrete yet consistent higher surface temperature of the meadow during the late autumn and early winter months was also uncovered. One of the postulated reasons for this phenomenon is background heat production via biological activity in the soil or the meadow acting as a wind barrier. This opens up the possibility of a beneficial effect of meadows on urban heat balance and thermal comfort in winter. This effect ceased when the annual maintenance was undertaken. Future cities in their effort to reduce their environmental imprint and combat negative effects of urbanisation should consider dense multi-layered meadows as a credible alternative to trees as they promise an efficient equilibrium of the urban heat balance than trees, at least in the Cfb climate studied.

Additional work was undertaken to investigate the possibility of predicting naturalistic meadows' regulating services. In Chapter 7, the microclimatic simulation software Envi-Met was tested in order to gauge how realistic it was in modelling herbaceous vegetation; the main comparison criteria was surface temperature due to the availability of field measurements from the previous chapter. In the general validation phase, it was demonstrated that Envi-Met produced surface temperatures that were consistent with reality, notably underneath trees and for exposed concrete. However, it seemed that the surface temperature of exposed turf was too high, at least when compared with maximal recorded temperatures from another study. In the herbaceous vegetation validation phase, the base model was simplified and two different grass and forb covers were compared in two different climatic scenarios for which data was available: a hot and dry scenario and a temperate oceanic (thermographic data from Chapter 6). In both cases, the base assumptions and the model, as is, produced satisfactory results except for volumetric water content. Envi-Met proved it could handle appropriately herbaceous vegetation and, with some tweaking, SuDS schemes could also be implemented into the software to evaluate their microclimatic effects.

8.2 Meadow vegetation and liveability

In the introductory chapter, liveability was defined as an environment's capacity to bring well-being through fulfilment of basic and higher order needs. A naturalistic urban meadow which was already a sustainable and financial sound type of vegetation was studied for its capacity to deliver cultural and regulating ecosystem services. Framed in an anthropocentric way, these ecosystem services may be defined as the benefits human may derive directly or indirectly from the existence and output of a biological community and its physical environment.

This work has linked the presence of an urban naturalistic meadow with a few indicators of liveability. From a psychological perspective, the urban meadow improved aesthetic and landscape appreciation and satisfaction within the built environment. This delivery of cultural ecosystem services was further demonstrated through the link between sensory interaction with the vegetated scheme and improvement of thermal comfort beyond predicted by thermal indices. From this point of view liveability was improved by providing a more pleasing streetscape, which could stimulate walking behaviour and favour restoration of intellectual fatigue. Perception of the scheme has been suggested to increase tolerance to thermal discomfort, thus providing less strenuous outdoor living conditions. A marked increase in "happiness" was noted which support the narrative that the meadow has increased psychological well-being. The delivery of regulating services were demonstrated by the thermography results which highlighted the UHI combating effect of dense multi-storey herbaceous vegetation. The regulating services are on a par, if not more efficient, than other types of vegetation. This novel conclusion, which goes against prior assumptions, adds meadow as a valid component of UHI mitigation measures. The original results presented in this body of work demonstrate meadow vegetation's capacity to make a city more liveable, thermally and aesthetically.

Two studies complemented this core work on ecosystem services production, namely the investigation of thermal preference and expectation and the pilot study on Envi-Met. Envi-Met validation was necessary to allow researchers to model herbaceous vegetation on large scales and predict accurately their regulating services and had not yet been undertaken in the literature. The visual questionnaire was a stepping stone towards understanding psychological components of thermal comfort while proving that thermal schemata existed in the absence of environmental stimulation. Eventually, understanding the perceptual and climatic influence of greenery on the sensation of thermal comfort might aid in improving the latter hence contributing to goals of liveability.

8.3 Limitations of the body of research

The research presented throughout this thesis presents a number of shortcomings. The thermal comfort chapter could have benefited from having on-site microclimatic data rather than a nearby rooftop weather station. This would have improved the precision of the Physiological Equivalent Temperature (thermal comfort index) used. In hindsight, an additional question should have been added to the questionnaire such as: “At the moment, would you prefer it warmer, the way it is or colder?”. It would have added a directionality to respondents’ Actual Sensation Vote and would have helped in the analysis of thermal sensations. In the visual questionnaire, two visualisations resembled each other too closely (meadow + trees and meadow + bushes + trees). Indeed, the canopy of the bushes and grasses were about the same height thereby creating little difference between both scenarios. This may have confused respondents and therefore some level of caution must be used when looking at the distributions of responses.

There is no temporal overlap between the thermography measurements and the thermal comfort assessments. As such, the improvement in thermal sensation may be discussed with mention to the psychological benefits derived from the experience of the scheme but not with the potential improvement of the microclimatic context. It is unfortunate that the regulating and cultural ecosystem services could not be investigated simultaneously. Moreover, this link could have been suggested if the work on Envi-Met had been more advanced. Despite having a proof of concept that Envi-Met is realistic in its surface temperature output, more variables such as soil moisture and air temperature at different heights could have been added. Another key variable in the heat balance is water. Indeed, liquid water is transformed into gas by evaporation or transpiration in plants which effectively “removes” heat. The soil moisture sensors were not calibrate to the Grey to Green’s growing medium and thus could not be used as an indicator of the scheme’s use of water. If Envi-Met had been fully validated for modelling the Grey to Green then it could have been a way to bring the scheme’s microclimatic effect together and model its effect on the PET. This would have further improved the thermal comfort

8.4 Further research

As a new urban tool, it is evident that mixed perennial plantings require further studying in order to gain a systematic understanding of their microclimatic services. As the meadow matures and plants reach their optimal height and density surface temperature measurements should be replicated, particularly regarding the winter warming phenomenon which could further address liveability goals. A full characterisation of the hydraulic behaviour of the growing medium of the Grey to Green, as well as the application of various evapotranspiration estimation techniques would allow future researchers to determine the weighed contribution of shading, evaporation and transpiration to the temperature reduction benefits. This, in turn, would inform modellers using Envi-Met to refine the parameters necessary to replicate existing meadows and then use the software as a powerful prediction tool. Ultimately the goal is to achieve a good working knowledge of the situations when trees, meadows or other forms of vegetation may be most beneficial given a place's idiosyncrasies.

As a novel form of urban planting, mixed perennial plantings have shown promising results but knowledge on their internal dynamics and yearly rhythms is limited. Factors that were not considered as part of this study such as seasonal and ecological succession, biodiversity and support for invertebrate life need to be reported as they may provide additional support for the sustainability benefits derived from this type of scheme.

More research is needed to flesh out the existence, boundaries and interaction between various psychological factors. Given their interaction with landscape preference and appreciation, future methodologies ought to include degrees of quantifiable characteristics (naturalness, species diversity, design elements etc.) as well as diversify the set of landscape and weather scenarios presented to participants. It is expected that the moderating effect of expectations and preference on thermal judgement is itself mediated by personal factors (such as the climate of reference) and cultural factors. As such further studies should also pursue the aim of uncovering how nationality, membership to a sub-culture or group may influence these perceptions. It would shine the light on techniques or design styles that would improve, in a culturally and climatically relevant manner, the aesthetic experience, the satisfaction derived from meaningful places without necessarily improving the actual climatic conditions themselves; i.e. improve liveability of future cities.

8.5 Practical recommendations

- Meadow-like plantings composed of biodiverse tall-growing and overlaying perennial grasses and forbs should be preferred over turf grass for non-recreational amenities. Indeed, the former was shown to bring both meaningful cultural ecosystem services while providing significant UHI abatement benefits.
- Insofar as observed, a synergy between the SuDS function and the meadow's ecosystem function emerged. As such, this combination ought to be replicated, at least in Northern Cfb climates. Additionally, instead of installing green spaces which solely bring socio-cultural benefits, and perhaps biodiversity benefits, SuDS schemes such as the Grey to Green should be implemented; a recommendation in line with CIRIA's best practice advocacy.
- Owing to psychological preferences conserved through evolution and perhaps to a shift in cultural preferences, the introduction of vegetated spaces resembling "Nature" (with high degrees of naturalness) should be sought through notably the naturalistic planting style.
- Comparing appreciation of the Grey to Green scheme and results from the landscape preference questions, it seems that the complexity of the plantings was appreciated. The weighted contribution to preference of each geometrical element (low, medium or high growing) is yet unknown but it seems evident that designers ought to mix these vegetation types in a manner that fulfil the need for human fascination and seasonal changes as much as the need for visibility, extent, complexity and feeling of safety. While some of these notions may seem contradictory, design solutions should seek to offer varied ecological niches complementing the local urban setting. This recommendation is reinforced by the idea that, from a microclimatic standpoint, these different geometries contribute differently to make a place liveable. Thus, providing a locally appropriate combination of shrubs, herbaceous flora and trees might be the key to optimising liveability in cities.

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Appendix

1. Grey to Green: users' experience survey

Observation

Date Time Weather

Part 1: Type of user

Sex:	Male	Female

Age:	0-15	16-25	26-35	36-45	46-55	56+

Interviewee was

Walking or performing a task	Staying still or seated

How often do you pass by here?

First time	Every day	A few times per week	A few times per month

Are you here:

For work	For leisure	On an errand	To visit the site specifically

Part 2: The planting

The planting along this street is attractive

Disagree strongly	Tend to disagree	Neither agree/disagree	Tend to agree	Strongly agree

The planting along this street looks natural

Disagree strongly	Tend to disagree	Neither agree/disagree	Tend to agree	Strongly agree

This street looks nicer now that it has been planted

Disagree strongly	Tend to disagree	Neither agree/disagree	Tend to agree	Strongly agree

The planting along this street fits well within the surroundings

Disagree strongly	Tend to disagree	Neither agree/disagree	Tend to agree	Strongly agree

The plantings are maintained well

Disagree strongly	Tend to disagree	Neither agree/disagree	Tend to agree	Strongly agree

Overall, how would you rate the appearance of this new landscape and street design? On a scale of 1 – It looks really bad to 5 – it looks really great.

Have you changed your journey to pass by or through this area?	No	Yes

Would you like to see more of this type of greening around Sheffield?	No	Yes

Part 3: Safety and Pollution

The street and area feels safer with the new landscape

Disagree strongly	Tend to disagree	Neither agree/disagree	Tend to agree	Strongly agree

There is less danger to people from traffic and vehicles with the new landscape

Disagree strongly	Tend to disagree	Neither agree/disagree	Tend to agree	Strongly agree

There is less air pollution with the new landscape

Disagree strongly	Tend to disagree	Neither agree/disagree	Tend to agree	Strongly agree

I feel happy when I am walking along this street

Disagree strongly	Tend to disagree	Neither agree/disagree	Tend to agree	Strongly agree

Part 4: Street comfort

At the moment, do you find it:

Very cold	Cool	Neither cool nor warm	Warm	Very hot

What do you think of the wind at this moment?

No wind	Light Wind	OK	Windy	Too much wind

What do you think of the humidity at this moment?

Damp	OK	Dry

So would you are comfortable being outside right now?

Yes	No

2. Thermal preference and expectation visual questionnaire

2.1 Introductory comment

Green areas in cities can affect people in positive or negative ways. In particular, green areas are known to impact the local climate and thermal comfort which is the feeling of satisfaction (or dissatisfaction) you experience with the temperature of your environment.

With this in mind, we would like to ask you a few questions on your preference and levels of comfort within different urban green areas as if you had to walk through them either on your way to somewhere (work, grocery store, etc.) or for leisure.

The pictures of landscapes you will be seeing are just examples and are there to illustrate the different kinds of green spaces one may encounter in urban areas (may it be trees, flowering plants, shrubs or any combination thereof).

Most questions in this survey must be answered in order to move forward. If you have started the questionnaire but do not wish to pursue it until the end, you are free to do so without there being negative consequences. This survey should take you about 8 minutes to complete.

All answers are anonymous, hence participants cannot be identified and won't be identifiable at any point of this research. The data will be used as part of a Ph.D. thesis and will only be accessible to the Ph.D. researcher and his main supervisor. The data’s analysis might lead to scientific publications in academic or professional journals, conferences or seminars.

This research project has received Ethical Approval from the University of Sheffield. Should you require additional information or would like to withdraw your answers, please contact:
Adrien Lhomme-Duchadeuil
Department of Landscape, University of Sheffield Floor 9, Arts Tower, Western Bank, Sheffield, South Yorkshire, S10 2TN

Participant's understanding of the research

	I have read and understood the description written above.
	I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences.
	I understand that my responses will be anonymous and I will not be identified nor identifiable at any stage.

Participant's agreement to the research

	I agree to participate in the questionnaire.

2.2 Participant Information

In which age category are you?

0 - 17	18 - 25	26 - 35	26 - 35	36 - 45	46 – 55	56 - 65	66 +

Are you:

Male	Female	Other

What is your main occupation?

Student
Higher managerial
Lower managerial
Intermediate
Small employers and own account
Lower Supervisory and technical
Semi-routine
Routine
Never worker or long-term unemployed
Occupation not stated or inadequately described
Not classifiable for other reasons

The country where you grew up or where you have spent most time in your life will impact what type of climate and what type of landscape you are used to. We would therefore like to know where you are from.

In which **country** have you lived the most time in your life? [List of Countries]

Which **city** have you resided in most during this time? [Blank answer Box]

2.3 Landscape preference and views

Which one of these examples of urban landscapes below do you **prefer**?

Low Only	Low & Medium	Low & High	Low, Medium & High

Which one of these examples of urban landscapes below would you say is the most **aesthetically pleasing**?

Low Only	Low & Medium	Low & High	Low, Medium & High

Which one of these examples of urban landscapes would you say looks the most **natural**?

Low Only	Low & Medium	Low & High	Low, Medium & High

2.4 Thermal preference in green spaces

The weather is a big part of how comfortable one feels when being and walking outdoors. In this part of the survey, you will be shown a walkway with different green space configurations and asked where you expect to feel most thermally comfortable to walk through or being in if you were exposed to different weather scenarios. It is assumed these situations happen during the summer or the hot season of the year in the city you have spent most of your time. The weather scenarios will be described using a combination of two adjectives: windy/still, warm/cool. These have been chosen because they are the main drivers of outdoor comfort.

To aid in your comprehension, the following pictograms will be used:

Windy conditions

Still conditions

Warm conditions

Cool conditions

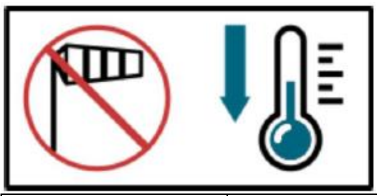
Participant's understanding of weather descriptions and pictograms

	I have read and understood how the scenarios will be described.

On a still and warm summer day, I would prefer walking or being in:

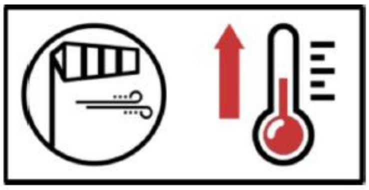
No vegetation	Low Only	Low & Medium	Low & High	Low, Medium & High

On a still and cool summer day, I would prefer walking or being in:



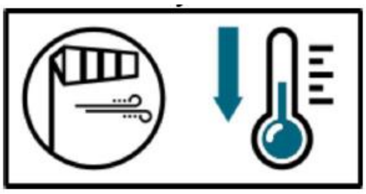
No vegetation	Low Only	Low & Medium	Low & High	Low, Medium & High

On a windy and warm summer day, I would prefer walking or being in:



No vegetation	Low Only	Low & Medium	Low & High	Low, Medium & High

On a windy and cool summer day, I would prefer walking or being in:



No vegetation	Low Only	Low & Medium	Low & High	Low, Medium & High

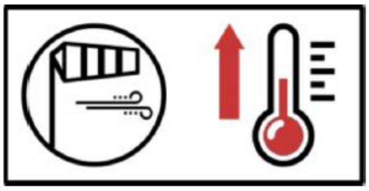
2.5 Thermal expectation

The following set of questions will ask you about your **expectations** with regards to thermal comfort.

On a still and warm summer day, I expect which situation shown below to be the **warmest**:

No vegetation	Low Only	Low & Medium	Low & High	Low, Medium & High

On a windy and warm summer day, I expect which situation shown below to be the **warmest**:

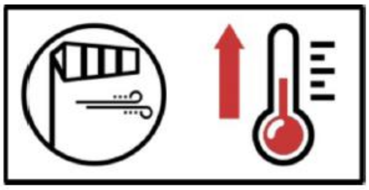


No vegetation	Low Only	Low & Medium	Low & High	Low, Medium & High

On a still and warm summer day, I expect which situation shown below to be the **most comfortable**:

No vegetation	Low Only	Low & Medium	Low & High	Low, Medium & High

On a windy and warm summer day, I expect which situation shown below to be the **most comfortable**:



No vegetation	Low Only	Low & Medium	Low & High	Low, Medium & High