The Hidden Landscape

On fine-scale green structure and its role in regulating ecosystem services in the urban environment

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The Hidden Landscape. On fine-scale green structure and its role in regulating ecosystem services in the urban environment.

Abstract

The thesis investigates and highlights the role of fine scale green structure in the urban landscape with regards to the regulating ecosystem services of runoff mitigation, wind speed regulation and modification to mean radiant temperatures. The analysis was based on case studies in southern Sweden, projecting from a flooding incident in the Höjeå river catchment in 2007 and the current seafront development of Lomma Harbour and similar schemes in the Öresund region. The aim has been to explore the potential of how seemingly fine scale green structure may contribute to regulating ecosystem services and thereby play an important role to SuDS (sustainable drainage systems), the urban microclimate and climate responsive design. Part of the aim has been to retrieve this information through quantitative indices and computational modelling, assuming that a numerical approach can produce comparative, rigorous and perceptible outcomes that act as efficient communication tools for e.g. city officials, planners, landscape architects, etc. The work combined a historical approach as well as computational modelling of numerical and tangible indices to shed some light on the hidden processes of regulating ecosystem services of fine-scale green structure. The SCS-CN approach was used for estimating surface runoff and ENVI-met for green structure influences on microclimate. It was found that within the green infrastructure network, individual configurations of green structure elements often influenced regulating ecosystem services beyond their proportionate size. Their influence depended in turn on place-specificity and contextual characteristics of e.g. geographical location, time of year, site spatial configuration and architectural composition. This is discussed with regard to urban densification (spatial), climate change and sustainable development and how the two tools used here can help in green infrastructure planning. The results are also discussed from a qualitative angle, introducing the question of how the collective configuration of dispersed green structure can contribute to a resilient green infrastructure in the urban landscape.

Keywords: Urban ecology, SuDS, urban microclimate, resilience, pattern-process design, climate responsive design

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The way things look is not always the way things are. This fact should be cause for consternation among those who are interested in the management of ecological systems. A highly functional landscape structure may go unnoticed - even by people who depend upon its function.

Joan Iverson Nassauer, 1992

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Deak, J. & Bucht, E. (2011) Planning for climate change: the role of indigenous blue infrastructure, with a case study in Sweden. *Town Planning Review*, 86(11), 669-685.

II Deak Sjöman, J. & Gill, S.E. (2014) Residential runoff – the role of spatial density and surface cover, with a case study in the Höjeå river catchment, southern Sweden. *Urban Forestry & Urban Greening*, 13, 304-314.

III Deak Sjöman, J., Sjöman, H. & Johansson, E. Microclimatic qualities of local green structure. Under submission to *Landscape and Urban Planning*.

IV Deak Sjöman, J., Hirons, A. & Sjöman, H. (2015) Branch area index of solitaire trees – its use for designing with regulating ecosystem services. Journal of Environmental Quality, doi:10.2134/jeq2015.02.0069

My contribution to Papers I-IV was as follows:

I The theoretical framework was introduced and developed by Eivor Bucht. I compiled the following desk studies and was responsible for the composition and writing of the paper.

II I developed the theoretical framework and the research design, and also carried out the computational modelling, the composition of the paper and wrote the text of the paper. Susannah Gill assisted in introducing the SCS-CN approach and in providing beneficial feedback throughout the writing process.

III I developed the theoretical framework and the research design, and also carried out the computational modelling, the composition of the paper and wrote the text of the paper. Henrik Sjöman assisted with valuable advice with regard to tree species selection and with technical assistance during data collection at the Hørsholm Arboretum, Denmark. Erik Johansson assisted in introducing the ENVI-met modelling approach, in providing helpful support throughout the modelling process and in giving beneficial feedback throughout the writing process.

IV I developed the theoretical framework and research design, and also carried out the computational modelling, the composition of the paper and wrote the text of the paper. Henrik Sjöman assisted with valuable advice with regard to tree species selection and with technical assistance during data collection at the Hørsholm Arboretum, Denmark. Andrew Hirons contributed help with all statistical analyses of the branch area indices.

Abbreviations and definitions of terms and concepts

Dispersed green structure	The dispersed pattern of individual and fine-scale *elements* of vegetation, water and permeable surface/soils existing within the densely built-up urban landscape, irrespective of public or private realm. This includes *e.g.* street trees, small-scale water bodies, swales, road verge/median planting, patches of porous asphalt, green roofs, *etc.* (Figure 1). Disperse green structure thus constitutes the pattern of the individual elements of green infrastructure.
Green space	Open *spaces* in urban areas comprising a configuration of vegetation and permeable materials, and sometimes water features (*i.e.* bodies of water).
Green infrastructure	The ecological system-based *network* consisting of vegetation, permeable surfaces/sub-layers and water connecting urban and rural landscapes. In Swedish literature, green infrastructure in this urban context is sometimes also referred to as green-blue infrastructure[1].
PET	Physiologically Equivalent Temperature (PET) is a value indicating how the human body physiologically perceives

[1]See *e.g.* Olofsdotter *et* al. (2012) and Berg *et al*. (2013). The concept of green infrastructure as described in planning guidance from *e.g.* North America (USEPA, 2014) and in the UK (Natural England, 2013) also differs from the green infrastructure concept defined by the Swedish Environmental Protection Agency (Swedish Environmental Protection Agency, 2012). With a primary focus on biodiversity and recreational values, the Swedish Environmental Protection Agency has opted to exclude *e.g.* agricultural land, and ruderal/vacant land from the green infrastructure concept.

	thermal comfort (*e.g*. how the body perceives heat or cold depending on clothing, surrounding radiation, wind, *etc*.)
Strategic green structure	The term 'strategic [planted, positioned, placed] green structure' is used throughout the thesis and refers to how green structure may be incorporated in a site and place specific context with consideration to the functions and services of runoff mitigation, wind speed regulation and mean radiant temperature modification. The term implies critical observation of where and why fine-scale elements of green structure need to be carefully incorporated in the built-up urban landscape to fulfil the benefits expected with ecosystem services – especially when surface area and space seem to be restricted.
Structural soil	The term structural soil refers to the medium used as sub-layer construction in pavement systems; allowing for vehicle and pedestrian traffic load while still permitting root growth for *e.g*. trees.
SuDS	Sustainable drainage systems (SuDS) are storm water design and management that aim to mimic natural systems in collecting, storing and cleaning surface runoff thus releasing the water slowly back into the environment.
Tmrt	Mean radiant temperature (Tmrt) is the combined total sum of shortwave and longwave radiation fluxes to which the human body is exposed and has the strongest influence on thermal comfort. By determining Tmrt for a given site, it is possible to calculate the exact physiologically equivalent temperature (PET).


a
b
c
d
e
f

Figure 1. Examples of fine-scale elements of green structure in the urban landscape. In this thesis the collective configuration of these elements are referred to as *disperse green structure*. Above examples illustrate street trees/trees in paved urban environments (A), lawn, hedges, trees *etc*. as found in *e.g*. residential gardens and courtyards (B), planting in the urban street scape, *e.g*. parking lots and along road verges (C), green roofs (D), climbers/green walls (E), porous/permeable surface materials such as *e.g*. porous asphalt (F), vertical installations (G), permeable sub-layers such as *e.g*. structural soil (H), raingardens and swales (I), ruderal vegetation in vacant plots (J).

1 Introduction

Vegetation has been used to regulate local climate conditions for centuries in many different situations. The most notable examples of this are found in the urban periphery, the agricultural landscape and the domestic garden (Gustavsson & Ingelög, 1994; Sullivan, 2002). Windbreak planting for thermal comfort and crop protection in the winter season and shade trees for cooling and breeze effects in the summer illustrate how vegetation has been used in the cultural landscape and for the everyday wellbeing of people. In the designed landscapes and gardens of Moorish Spain, Ancient Mesopotamia or traditional Japan, water features and porous surface materials (such as shale and gravel) were used not only for aesthetic qualities, but also for functional needs for cooling and to retain rainwater (Jellicoe, 1995; Sullivan, 2002). However, with increasing dependence on engineered solutions in buildings, reliance and knowledge of how vegetation can be used has diminished (Hough, 2004). Although much emphasis is placed on mitigation and adaptation to climate change in contemporary urban planning, solutions for fully incorporating green structure in tandem to built structure, or how spatial patterns influence climate conditions, are seldom used and predominantly ignored (Eliasson, 2000; Mills, 2006; Wong *et al*., 2011).

Over the years, an extensive knowledge bank has been built up from studies of green structure and regulating ecosystem services. A number of research studies show *e.g*. how urban green space can help to decrease surface runoff (Xiao & McPherson, 2002), mitigate the urban heat island effect and thermal distress (Eliasson & Upmanis, 2000; Lafortezza *et al*., 2009) and lower the energy use in buildings (Akbari *et al*., 2001; Castleton *et al*., 2010). Other studies show how permeable surfaces and sub-layer constructions can reduce excessive runoff from various precipitation events (Brattebo & Booth, 2003). Climate modelling studies and urban morphological assessments have helped provide a comprehensive understanding of the contribution of urban green space to a comfortable microclimate and to mitigating and adapting to future climate change (Dimoudi & Nikolopoulou, 2003; Gill *et al*., 2007). This knowledge has undoubtedly helped place the role of vegetation and permeable surface materials at the forefront in discussions of sustainable development (*e.g*. Department for Communities and Local Government, 2012; IEEP and Milieu, 2013; USEPA, 2014; Boverket, 2014), and has resulted in quantification of green space values through evaluation implements such as Green Space Ratio (in the European

Union), the Sustainable Sites Initiative (in the USA), and the i-Tree tool (becoming more popular world-wide) (SSI, 2009; Kazmierczak & Carter, 2010; USDA, 2014).

However, green building certification programmes and green space evaluation methods such as LEED and the Green Space Ratio often shed limited light on how hard and soft landscaping during in site-level implementations correlates to the context of surrounding areas and to the interdependent relationship between urban and rural landscapes (as illustrated in *e.g.* USGBC, 2014; Green Area Ratio, 2014). Certification programmes, *e.g.* in Sweden, often reflect a general perspective on green space design and the same parameters are applied independent of geographical context (Emanuelsson & Persson, 2014). This in turn may have adverse effects on *e.g.* storm water planning and other ecosystem functions such as biodiversity, where characteristics (at site level and of neighbouring areas) and connectivity to the surrounding landscape are essential (Gyllin, 2001). Ignoring the functional relationship between site level and the geographically larger landscape may further contribute to planners and architects misconceiving small-scale capacity and quality (Pickett & Cadenasso, 2008). Instead, attention is given to gradients of infill development, built density and available surface area, aspects that most likely impinge on individual green structure elements and green space decision making (Jim, 2004).

In Sweden, tangible, quantitative information on how green structures can contribute as integrated building components to buildings and grey infrastructure is either weak or not contextualised to the given situation (*e.g.* Lomma kommun, 2002; Miljöprogram SYD, 2009; Stockholms stad, 2011). How to integrate green structure when space is limited and how this correlates to surrounding landscape functions is especially interesting in areas subjected to infill development or smart growth, where intelligent approaches to green structure implementation may create multiple benefits. Based on the current debate on infill development and developing spatially denser neighbourhoods (Gordon & Richardson, 1997; Handy, 2005; Kyttä *et al.*, 2013), a central focus of this thesis was thus to review how different spatial densities affect storm water runoff and how small-scale efforts at green structure implementation can help achieve a resilient web of green infrastructure even in denser urban cores. The role of trees is another important aspect, owing to their pre-eminent qualities and disproportionate contribution of ecosystem services (compared with the small area individual trees occupy) in the urban landscape (Dwyer *et al.*, 1991; Jim & Chen, 2003; Tyrväinen *et al.*, 2005; Manning *et al.*, 2006), but also due to the methodological framework applied in the studies reported in Papers II, III and IV (see Chapter 6).

The role of regulating ecosystem services was examined in this thesis using both quantitative and qualitative approaches, against a background of contextual discussions on how dispersed green structure can help mitigate surface runoff, regulate wind speed and modify mean radiant temperatures. A secondary objective, primarily dealt with in this summarising essay, was to examine the question of a collective configuration of dispersed green structure and its contribution to a sustainable urban landscape. Such configurative processes may not be so easily perceptible to begin with, but need to be revealed and made tangible (James *et al*., 2009).

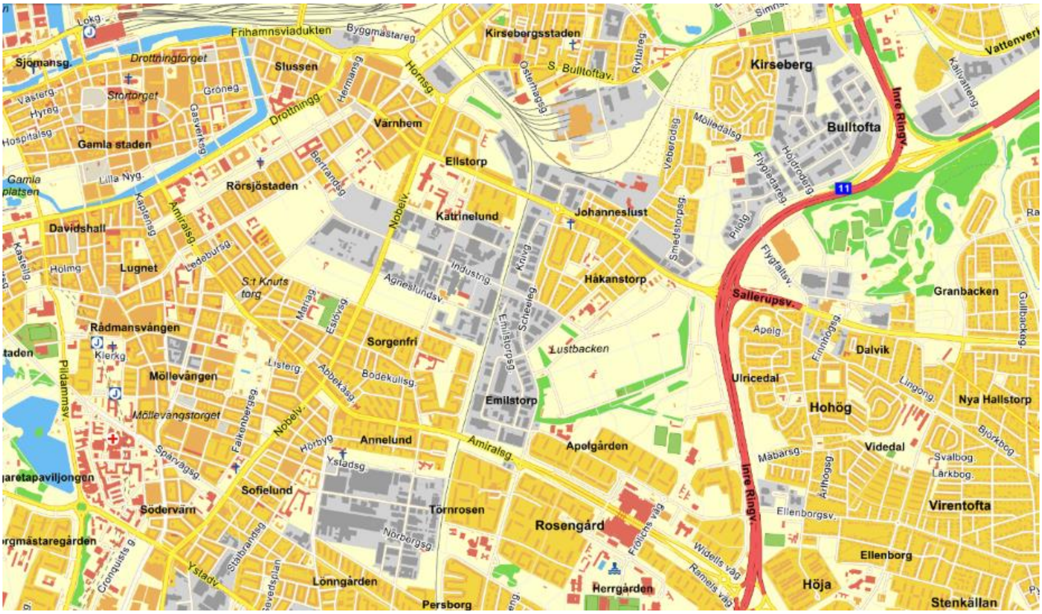
1.1 Why highlight the role of dispersed green structure?

The reasons for this question are manifold. It broadly arises from the proposal that more knowledge is needed on how the seemingly fragmented green structures across the urban landscape contribute to a resilient approach to urban development. The following sections describe the problematical context of disperse green structure in the urban landscape and explain why disperse green structure constitutes an interesting subject area.

The spatial distribution of fine-scale structure and its connection to landscape function create some complexity. Interspersed within the built-up urban landscape, green structure is embedded in both private and public land ownership (Attwell, 2000; Lundgren Alm, 2001; Young, 2011). In official urban classification maps, *e.g*. in Sweden, residential gardens, street trees and other dispersed urban green structures are categorised as built-up land cover (Colding, 2011) (Figure 2). The very existence of green infrastructural elements is either ignored or taken for granted. From an aerial perspective dispersed green structure may look highly fragmented, with a scattering of small-scale patches including street corner greenery, strips of road verge planting, courtyard green spaces, pocket parks, street trees *etc*. Although these are abundant in number, the purist ecologist may consider them too fragmented to contribute to any long-standing ecological quality (and subsequent benefits to biodiversity) (McDonnell *et al*., 1997; Niemelä, 1999; Forman, 2008). In the mindset of a strategic planner adhering to the contemporary paradigm of urban densification and smart growth, dispersed green structure may well fit in with a vision of sustainably engineered green space (Villarreal *et al*., 2004) or it may well succumb to make way for urban infill (Beer *et al*., 2003; Pauleit *et al*., 2005).

Furthermore, the persistence of dispersed green structure is vulnerable and could over time become very inconsistent (Forman, 2008). In the private realm of residential gardens, homeowners do as they please, inevitably making domestic green space highly varied (Gill, 2006). This involves everything from planting young trees and growing vegetables to removing mature trees and replacing permeable surface cover with hard-paved patios and driveways. In new development schemes, *e.g*. commercial retail, business and residential areas, the design and implementation of green structure usually conforms to a dispersed spatial layout. This is partly due to the blueprint of buildings and roads, but also because in most cases "green structure follows built structure" and is only considered in detail at the very final phase of the building process. Today, many building engineers have built up a robust technical dataset over time and use *e.g*. U-factors for windows, R-values for building envelopes, specifications for ventilation systems *etc*. (*e.g*. the quantitative indices in the environmental assessment methods USGBC, 2014; BREEAM, 2014). In contrast, many landscape architects struggle for equivalent indices to help justify why green structure should be incorporated in tandem with built structure and much earlier in the planning and building process. Understanding how different soft and hard landscaping materials function as eco-technical components and deliver ecosystem services quite differently may become essential in communicating the values of green structure and long-term sustainability.

Figure 2 (next page). In official urban classification maps in *e.g*. Sweden, residential gardens, cemeteries, road side planting and other dispersed green structures are categorised as built-up land cover (top), whilst an aerial photograph of the same area (below), illustrate a more accurate representation of visible green structures. *Photo: Eniro and Metria*


Frihamnsviadukten
Byggmästareg.
Kirsebergsstaden
S. Bulltoftav.
Kirseberg
Sjömansg.
Drottningtorget
Slussen
Hermansg.
Hornsg.
Stortorget
Gröneg.
Drottningg.
Värnhem
Mölledalsg.
Bulltofta
Inre Ringv.
Gamla staden
Ellstorp
Rörsjöstaden
Bertrandsg.
Lilla Nyg.
Davidshall
Katrinelund
Johanneslust
Nobelv.
Amiralsg.
Lugnet
Industrig.
Håkanstorp
S:t Knuts torg
Agneslundsv.
Sallerupsv.
Granbacken
Rådmansvången
Sorgenfri
Lustbacken
Dalvik
Möllevången
Emilstorp
Ulricedal
Hohög
Nya Hallstorp
Möllevångstorget
Pildammsv.
Annelund
Apelgården
Videdal
Sofielund
Ystadsg.
Virentofta
Södervärn
Tornrosen
Rosengård
Ellenborg
Lönngården
Herrgården
Höja
Persborg
Stenkällan

Finally, urban growth, excessive energy use, weather extremes and climate change are cited as great challenges to sustainable development in the near future (Hough, 2004; Niemelä, 2011). Although it cannot be regarded as a panacea to these difficulties, green infrastructure is considered valuable in helping to mitigate some of these adverse effects (*e.g*. flooding, high temperatures, building energy use), whilst providing cultural, ecological and economic benefits (Benedict & McMahon, 2006; Natural England, 2013; USEPA, 2014). In the case of surface runoff, incorporating sustainable drainage systems on available land becomes especially challenging. However, dispersed green structure provides the urban landscape with the means to mimic natural systems, *i.e*. to infiltrate and retain rainfall in an even distribution throughout the urban landscape and not only in targeted zones, *e.g*. wetlands, detention basins and retention ponds (Day & Dickinson, 2008). The approach of recognising the benefits of spatially fragmented (scattered) green structure for climate adaptation and mitigation may thus allow adaptive strategies to embrace the urban landscape in its entirety and not only through particular measures involving larger green areas and parks. Although the spatial configuration of dispersed green structure in an aerial view may appear scattered, its functional connectivity may support new innovative approaches to *e.g*. urban planning (Tanner *et al*., 2014). This may challenge planners to re-view invisible, albeit occurring, temporal and spatial arrangements and interactions (Magnuson, 1990), and makes the research area of disperse green structure an interesting area to explore.

1.2 The hidden landscape

Numerous studies show that *landscape* is more than meets the eye and that configurations of elements and processes in the landscape may affect and influence social-ecological experiences and relationships, even if they are seemingly hidden to visual perception (Porteous, 1985; Lee & Ingold, 2006; Scott *et al*., 2009). According to Olwig (1996), the substantive meaning of landscape goes beyond being purely an aesthetic representation and natural scenery. Instead, landscape reflects the entity and process of community, culture, labour, social practice, politics, law, *etc*. (Olwig, 1996, 2005) and becomes "to an exclusively human way of positioning oneself in relation to the external environment" (Kirchhoff *et al*., 2012: p. 42).

Seeing, or deconstructing, the surrounding environment into something recognisable to common perception (or suited to ambitions) has governed much landscape planning and design in the industrialised world – not at least through the modernist approaches of the Twentieth Century (Burns & Kahn, 2005; Beauregard, 2005). Landscapes have been erased, ignored, enhanced and selectively chosen to subsequently function as a premeditated stage for development or conservation (Beauregard, 2005). Although some measures may have corresponded to seemingly sustainable initiatives, others have occurred with disregard for the legacies and processes inherent to that landscape (Spirn, 1984, 2005). Recognising past landscapes in present contexts challenges one to see inherent morphology, boundaries and movement routes layered in time (Dobson, 2011). "Revealing history" in landscapes thus goes beyond identifying designated sites and listed buildings. Rather, it aims to interpret ubiquitous traces and cultural associations that not only help create a sense of place and identity (Dobson & Selman, 2014), but also communicate past social-ecological processes that can guide present and future decision making (Antrop, 2005).

Nassauer (1992: p. 239) discusses the role of landscape aesthetics and the affective response of people, concluding that "what we see influences what we think belongs in the landscape". Although hydrological fluctuations can be visually revealed with the help of installations and the design of rain gardens, detention ponds, water channels, *etc*., sub-surface conditions and lateral flows in the soil remain hidden to immediate perception. Taking the role of regulating ecosystem services – in particular that of temperature modification and wind speed regulation – the flows and dynamic processes influenced and moderated by green structure are often not visible to the naked eye. By not seeing these subtle processes, it may be difficult to recognise their influence and strategic place in broader contextual circumstances. Instead, people use their proximal senses and multi-sensory experience (as described in *e.g*. Irigaray, 1999) and relate to the microclimatic effects surrounding them on a much smaller and site-based scale, *i.e*. through the experience of thermal comfort rather than vision. Revealing the hidden landscape of microclimate influence to landscape planners and designers can thus be addressed from the phenomenological point of view presented in *e.g.* Böhme (1995) and Pallasmaa (2005) and elaborately described and developed in Sandra Lenzhölzer's doctoral thesis *Designing Atmospheres* (2010).

1.2.1 Uncovering invisible landscapes – tools and concepts

According to Hill (2005), the late Twentieth Century paradigm shift in ecology towards an appreciation of greater complexity in ecosystem behaviour and non-equilibrium of social-ecological systems may help pave the way for alternative planning and design actions of understanding and "revealing" not so easily detected landscape configurations and processes. With the example of "site" as landscape configuration, Hill (2005) exemplifies how *e.g.* the permeability of movements (energy, materials, organisms, *etc.*) can be exposed through metaphorical exchange resulting from transdisciplinary interactions. This in turn can initiate fresh and innovative perspectives of a given site and subsequently of the configurations that make up place. Novel metaphors, alternative concepts, terms and vocabulary may thus arise to help guide landscape planning and design (Hill, 2005; Kahn, 2005).

However, it is important not to underestimate the role of visual representation and critical observation (Moore, 2010) and to understand that "people [may] not know how to see ecological quality directly (Nassauer, 1995a: p. 161). A study by Qui *et al.* (2013) found that specific features and configurations of green structure indeed affected people's preference for urban green space and their perception of green space potential to biodiversity and recreation. While local interaction and reaching out with information and environmental education to the public are seen as important mechanisms for sustainable urban development (Burgess *et al.*, 1988; Colding *et al.*, 2006), appreciating that ecological quality can only be seen "through our cultural lenses" is just as important (Nassauer, 1995b).

Although a general consensus on sustainable development inhabits the greater part of contemporary landscape architecture (IFLA, 2014), understanding *how* social-ecological systems and *e.g.* ecosystem services can be brought into being through design and innovative planning can still remain ambiguous in the design process (Nassauer, 1995a; Phillips, 2003). Tools to help illuminate how processes are innate to patterns and individual structures in the urban landscape, *e.g.* landscape ecology (Pickett & Cadenasso, 2008; Ahern, 2013), network-based analyses (Bodin and Zetterberg, 2010) and computational modelling (*e.g.* Bruse, 2009), can be seen as operative approaches in this respect. However, actively observing and learning by on-site experiences also creates the necessary building blocks for a comprehensive understanding of social-ecological systems – in interplay at site level and through individual configurations (Rafaelli & Frid, 2010; Nielsen, 2011). Returning to the topic of past knowledge and traditional practice of microclimate planning (as mentioned in the beginning of this chapter) and how to incorporate green structure into surrounding contexts, it becomes evident that knowledge itself can be the visible vehicle. By using available techniques such as climate modelling tools, it may be possible to contribute knowledge that makes the invisible landscape more visible.

1.3 Background to case study areas and critical approaches

1.3.1 Höjeå river catchment and the flooding of 2007

In summer 2007, prolonged and heavy rainfall events caused severe flooding in southern Sweden. The Höjeå river catchment, comprising Lund, Staffanstorp and Lomma municipalities, all suffered major financial losses owing to damage to property and infrastructure. Located in the Öresund region (comprising eastern Denmark and the most southern tip of Sweden) the Höjeå catchment is situated within an area strongly affected by urbanisation, with continuous development of infrastructure and of commercial retail, office and residential areas (Figure 3). As part of the development process, the role of sustainable storm water planning has gained increasing recognition in many of the new residential and mixed-use developments (*e.g*. Lomma kommun, 2002; Miljöprogram SYD, 2009; Stockholms stad, 2011). However, the Swedish term for sustainable drainage systems (SuDS) – *öppen dagvattenhantering [open storm water management]* – creates complexity and sometimes a misconception of what the concept could entail. Unfortunately, the Swedish SuDS concept all too often becomes associated solely with visible water bodies and structures that require space in terms of available surface area (*e.g*. Miljöprogram SYD, 2009). Instead of forming a resource and a four-dimensional asset in space and time, the Swedish SuDS concept creates a rather compromised approach and, due to competition for available surface area, sustainable storm water drainage implementation runs the risk of becoming secondary to other utilities and functional structures. In tandem with planning policies on smart growth and urban densification (Williams *et al*., 2013) or in existing urban centres with a high built-up density, such a perspective further complicates sustainable storm water drainage implementation. There are of course significant exceptions of integrated approaches to SuDS in Sweden, *e.g*. the inner city residential area Augustenborg in Malmö (Klimatanpassningsportalen, 2013) or some of the tree planting schemes in Stockholm (Figure 4).

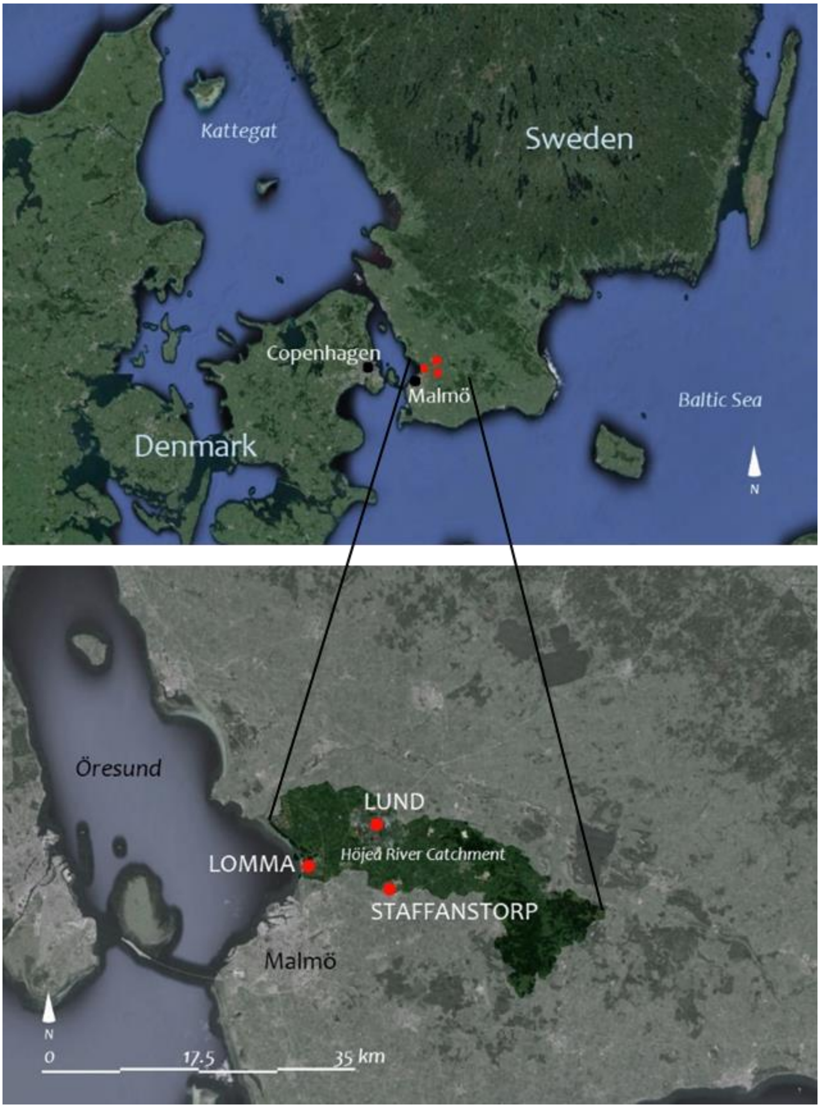


Figure 3. Aerial photograph of the case study area with Höjeå river catchment and urban areas of Lund, Staffanstorp and Lomma. © Lantmäteriet, i2014/764

Figure 4. An examples of SuDS where surface runoff is connected to the planting beds and the runoff is used as a resource to water the trees (Stockholm, Sweden) (Sjöman & Slagstedt, 2015).

In the Höjeå river catchment, urban growth and densification are prominent in the urban areas of Lund, Staffanstorp and Lomma. The municipality of Lund expects an increase of approx. 18 000 inhabitants in the next 10 years and is extending its urban volume through urban infill and new development spreading into the countryside and the surrounding agricultural landscape (Lunds kommun, 2014). Today, residential areas make up approx. 40% of the urban built-up land in Lund, Staffanstorp and Lomma. Within the private realm of residential space and domestic gardens, recent years have seen an accelerating trend for paving front lawns and extending patios with impermeable materials, leading to a further increase in surface runoff (Folty´n, 2011; Christiansson, 2012; Persson *et al*., 2012). Due to private land ownership, municipalities in Sweden face difficulty regarding interference in this matter, as no legal action of *e.g*. planning permission can be enforced to reduce the amount of additional impermeable surface sealing (compared with *e.g*. the UK, where such measures were enacted in 2008 (Hansard, 2008; Department of Communities and Local Government, 2008). Although public land offers greater potential for municipalities to control surface sealing, storm water solutions are seen as almost impossible to incorporate within the dense urban core. SuDS therefore predominantly entails large ponds or detention basins located in the urban periphery (Lunds kommun, 2010).

As a response to the flooding in 2007 and in order to encourage robust adaptation strategies in view of the likelihood of similar events in the future, an inter-municipal cooperation was initiated in that year including the municipalities of Lund, Staffanstorp and Lomma (Figure 5). The collaboration was named Höjeå Storm Water Group (now incorporated into Höjeå Water Council) (Höjeå Water Council, 2013a). Lomma, which is a smaller settlement than the city of Lund, is situated by the shores of Öresund (the strait between Denmark and Sweden) downstream of the Höjeå river, and is thus the destination of any runoff from upstream urban areas. Prior to negotiations with insurance companies and crisis intervention units, Lomma municipality experienced financial liabilities of SEK 29 million (approx. €3 million or $3.8 million) due to the flooding in 2007 – a great financial loss for a small municipality (Nilsson, 2013). Incorporating sustainable drainage systems and finding means to avoid future damage and financial losses is thus imperative to land use planning in Lomma. Similarly to Lund, Lomma is predicting an increase in its population within the next decade and during the past seven years has seen annual urban in-migration of approximately 500 people (Lomma kommun, 2014). Residential areas for new inhabitants are being developed, *e.g.* Lomma Harbour.

Figure 5. The flooding in Lomma municipality 2007 caused major financial losses where water flooded infrastructures and properties. The aerial photograph depicts the area of Lomma Golf Club. *Photo: Swedish Coast Guard.*

1.3.2 Lomma Harbour – microclimate and evaluation of green spaces

Lomma Harbour is a new mixed-use development on a former industrial harbour site next to the outlet of the Höjeå river and the shore of Öresund (Figure 6). The master plan was enacted in 2003 for a development covering a total area of 51 hectares and Lomma Harbour expects to see completion within the next 5-10 years. The aim is to create a spatially compact residential area with mixed-use possibilities for local commerce, a variety of residential housing with private courtyards and gardens, and inviting outdoor public spaces for different recreational purposes. As in similar contemporary developments in Sweden and internationally, the developers of Lomma Harbour aim to meet certain environmental goals such as low energy use in buildings and a recreational environment to the benefit of the community (Lomma kommun, 2003).

Figure 6. Aerial photograph of the Lomma Harbour development area in Lomma, Sweden.
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In 2009, Lomma municipality received government funding from the Delegation for Sustainable Cities to initiate a learning process of sustainable development based on iterative dialogue between the municipality and the major development companies (The Delegation for Sustainable Cities, 2010). The idea was to evaluate how the process of Lomma Harbour development could achieve continuous improvement, *i.e*. what could be learned from each building phase and how this experience could provide insights into the next phase. As part of designing this evaluation process, Lomma municipality established a collaboration with the Swedish University of Agricultural Sciences (SLU) in Alnarp and the International Institute for Industrial Environmental Economics at Lund University. This included discussions with the municipality and the developers on how green space could be used to reconcile and integrate the environmental targets for Lomma Harbour.

Local weather conditions and the microclimate of Lomma Harbour determine some of the possibilities to achieve a comfortable outdoor environment for recreational use, reduced energy use in buildings and less wear and tear on building materials (all of which are environmental goals). The average wind speed is 5.6 m/s (at 10 m above sea level) and winds can easily and often reach well over 8 m/s (Meteotest, 2010; LBS, 2012). The spatial pattern of the Lomma Harbour master plan adds to the complexity of microclimate conditions and hinders measures to meet some of the environmental targets (Figure 7). The plan is based on a typical Hippodamian grid – a concept originating from Ancient Greece designed to stimulate air flow through the city between the mountains and the sea (Sinou, 2011). In Scandinavia or in any other part of the world where a colder climate prevails for six months of the year, this spatial layout can be problematic with regard to wind speed and turbulence, creating wind-chill effects and thermal discomfort (Höppe, 1999). In terms of energy use in buildings, strong winds can increase heating demand during winter depending on the airtightness of the building enclosure (Bullen, 2000; Bagge, 2011). Nevertheless, surprisingly many new seafront development schemes in Sweden (with exception of the Bo01 area in Malmö) have adopted the grid plan for their spatial layout instead of the more staggered and broken pattern typical of traditional coastal settlements.

Figure 7. The spatial layout of the Lomma Harbour master plan illustrates a typical grid plan that from a microclimate point of view will help increase wind flow throughout the area and create warmer temperatures in the enclosed courtyard spaces. (Illustrationsplan, Brunnberg & Forshed arkitektkontor).

The spatial layout, the prevailing microclimate and the environmental goals of the Lomma Harbour development constitute a natural backdrop and incentive to delineate green structures as ‘eco-technological’ components and to provide much-needed ‘facts’, clear and tangible information on how urban green space can help contribute to sustainable development (James *et al*., 2009). Regulating ecosystem services from disperse green structures can help produce such concrete and numerical values (*e.g*. Xiao & McPherson, 2002; Bartens *et al*., 2009; Yahia & Johansson, 2014). The question in the case of Lomma Harbour is how green structure could help mitigate the adverse effects arising from the spatial layout of buildings and the road system, the strong cold winds in winter and rising temperature within confined areas in summer – factors that all affect a number of the environmental goals for the development.

2 Research aim and research questions

The general aim of this thesis was to explore the potential of fine-scale and individual configurations of green structure to contribute to the regulating ecosystem services of runoff mitigation, wind speed regulation and mean radiant temperature modification. The intention was to obtain this information through quantitative indices and computational modelling, assuming that a numerical approach can result in a comparative, rigorous and perceptible outcome which in turn can provide an efficient communication tool for *e.g.* city officials, planners, landscape architects, *etc.* (Tidwell & van den Brink, 2008; Holmarsdottir, 2011) (Papers II-IV).

Another aim of the thesis was to examine the modelling results from a qualitative angle, introducing the question of how the collective configuration of dispersed green structure can contribute to a resilient urban landscape and sustainable green infrastructure planning.

The overall methodological process in the thesis was linked to and motivated by the research aims and questions. The worked followed an iterative process, where the outcome of preceding inquiries helped give rise to new aims and questions. The conceptual diagram in Figure 8 illustrates the research aims and questions with regard to Papers I-IV and this thesis essay. The overarching research questions in the thesis can be summarised thus:

- What role does disperse and fine-scale green structure in urban built-up areas play with regard to runoff mitigation, wind speed regulation and mean radiant temperature modification?

- What possible difficulties and/or advantages do the computational models of the SCS-CN method and ENVI-met contribute to green infrastructure planning?

Specific objectives and additional research questions examined in each of Papers I-IV are described below.

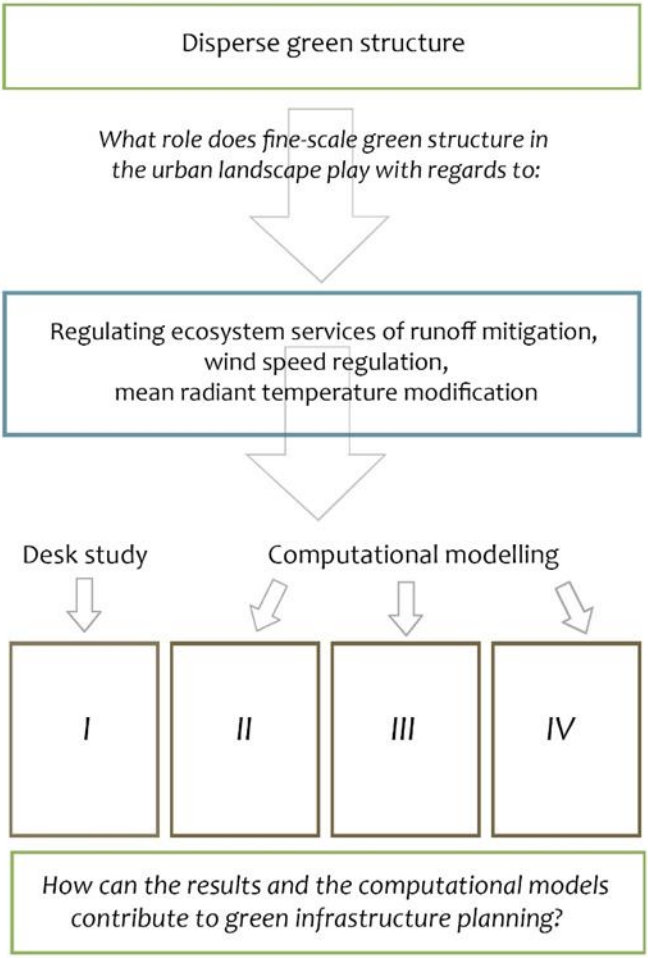


Figure 8. Conceptual diagram illustrating the overarching aim of the thesis.

2.1 Paper I

Paper I examined the historical context to an urban waterscape comprising fine-scale water structures and green structure and analysed how natural and indigenous landscape patterns can guide present urban planning in storm water management.

The study addressed the following questions:

- How has the pattern of indigenous water structures interlaced the urban landscape (of Lund) throughout history?

- Are the indigenous water structures of historical Lund recognised in current storm water planning?

The study partly examined the overarching research question of the thesis in general, *i.e.* how different regulating ecosystem services of fine-scale green structure elements may contribute to a resilient and sustainable approach in urban built-up landscapes.

2.2 Paper II

The aim of the Paper II was to establish quantitative indices for storm water runoff from different surface covers and green structures in residential areas. The importance of obtaining tangible and numerical values was identified in Paper I, where such an approach was not possible. Residential areas were chosen as the subject of study because they: 1) make up a large proportion of urban areas; 2) are an urban morphology type being predominantly developed in the study area; and 3) comprise fine-scale green structures and surface covers that over time might change in proportion and influence on regulating ecosystem services (runoff mitigation).

Due to an ongoing planning discourse of urban densification and smart growth, a further aim of Paper II was to investigate how densely built-up space influences surface runoff in a catchment perspective.

Using the SCS-CN approach, the study addressed the following questions:

- How do different densities of built-up space (in residential areas) affect the amount of runoff within the Höjeå river catchment area?

- What is the difference in runoff mitigation from tree cover in summer compared with winter?

- How do different surface covers and sub-layer constructions such as structural soils influence surface runoff in areas with different soil groups?

2.3 Paper III

Paper III examined how different combinations and strategic plantings of green structure, with specific focus on solitaire trees and fine-scale patches of green space, affected wind speed in winter and mean radiant temperature in summer in a mixed-use development area. The study was partly generated by the collaboration between Lomma municipality and SLU, and thus a secondary aim was to present the results of Paper III to representatives involved in the planning and building of Lomma Harbour.

Using the microclimate modelling software of ENVI-met, the study addressed the following questions:

- To what extent do different architectural make-up and strategic planting of fine-scale green structure, particularly trees, regulate microclimate conditions in a densely built-up urban area?

- Which synergistic and/or opposing effects arise due to seasonal changes in green structure regarding microclimate amelioration?

- What are the challenges concerning strategic positioning of trees with regard to microclimate amelioration in a densely built-up area?

2.4 Paper IV

Paper IV examined additional and emerging research questions arising in Paper III concerning how the different architectural make-up of trees influences the microclimate (and not only strategic positioning, which was the main focus in Paper III). The aim of Paper IV was thus to examine how different architectural arrangements of trees (due to species characteristics) affect wind speed and mean radiant temperature in a small-scale setting. Identifying how the architectural qualities of different tree species may affect microclimate conditions raised the related question of how individual elements of green structure can be seen as eco-technical components (similar to *e.g.* contemporary evaluations of different building materials and technical systems in current building practice (USGBC, 2014; BREEAM, 2014)).

While numerous studies have demonstrated how urban green space and individual trees can help ameliorate different microclimate qualities in summer (*e.g*. Shashua-Bar & Hoffman, 2000; Armson *et al*., 2012), limited research has been carried out on their role in winter conditions. In a temperate climate, understanding how different trees (with no leaf cover) may affect the microclimate in complex urban settings is of interest. Therefore Paper IV examined whether branch area index for solitaire trees could be used in microclimate simulations for wintertime conditions to reveal how different individual tree species may affect wind speed and mean radiant temperature. Using the microclimate modelling software of ENVI-met (Bruse, 2009) and a fictional case study area in the Öresund region, the study addressed the following questions:

- How does the branch area index of solitaire trees vary depending on species?
- To what extent do the different architectural qualities and branch area index of solitaire trees regulate the microclimate in winter (wind speed and mean radiant temperature)?
- What role can selection of different tree species play in climate response design in the built-up urban landscape?

3 Concepts and theoretical approaches related to the capacity and function of disperse green structure

The following sections present a number of concepts relevant to the subject area of dispersed green structure. These include green infrastructure, landscape ecology, the ecosystem approach, resilience studies and urban ecology. Although this review comprises distinct sections on each concept, research literature and *e.g*. government documents reveal that they are strongly interlinked. For instance, the current field of urban ecology is supported by a fusion of conceptual ideas of resilience, ecosystem services and the view of social-ecological systems, and the green infrastructure approach has its roots in landscape ecology and can be seen as a synthesis for green space planning within an urban ecology framework, *etc*. The aim of this review is to broadly discuss these concepts and critically analyse whether they provide a 'theoretical framework' on why and how dispersed green structures need to be highlighted and applied in current and future research on sustainable urban development.

With regard to *green infrastructure,* it is reviewed here both as a concept and as a planning approach. Although several other terms relate to the concept of green infrastructure, *e.g*. green structure, green space, urban forestry, the urban forest *etc*., the following discussion is limited to where green infrastructure as a conceptual idea of systems or networks has been specifically employed. This raises some complications as regards the Swedish concept/term *grönstruktur* (translated to 'green structure' in English), which can signify both individual elements of vegetation and permeable surface cover/sub-layer construction (Bucht & Persson, 1995), as well as a larger network of connected green space and water (Lundgren Alm *et al*., 2004; Sandström & Hedfors, 2009). In the following section, Swedish literature on green-structure (*grönstruktur*) is included when a network approach has been applied.

3.1 Green infrastructure – the concept

An aerial perspective on most urban landscapes will reveal a fabric of buildings and transport systems interlaced with a mosaic of vegetation and water. Depending on the quality and connectivity of individual green structure elements (above and below ground level), the interconnected mosaic of green space, water bodies and other unbuilt space makes up a system, like an electrical circuit board, that connects and influences the interdependency between urban and rural landscapes. While some of the elements and processes of this system network are visible to the eye, some are not. The system constitutes the essence of physical landscape structure and process, but also forms a conceptual backdrop to the planning term *green infrastructure*, which in the short span of a couple of decades has become a well-recognised approach in worldwide discourses on sustainable urban development (Davies *et al*., 2006; McDonald *et al*., 2005; European Commission, 2013). Numerous publications in both theoretical research and practice-orientated studies underpin its contribution as a multifunctional concept to address both current and future challenges to sustainable land use development and management – from broad national and regional scales down to local neighbourhood initiatives and individual site-level projects (Davies *et al*., 2006; Kambites & Owen, 2006; The North West Green Infrastructure Think Tank, 2008; Pauleit *et al*., 2011). Green infrastructure is valued for its economic, ecological and social values, regardless of public or private land ownership (Lundgren Alm, 2001; Benedict & McMahon, 2006; Davies *et al*., 2006).

The seminal definition developed in North America by Benedict and McMahon (2002) embraces the concept of green infrastructure as a diversified and multifunctional network of green spaces linking urban and rural landscapes. It constitutes a system of hubs, links and sites incorporating *e.g*. forests, agricultural land, waterways, parks, woodlands, gardens, swales, street trees *etc*. (Benedict & McMahon, 2006). In some studies and reports, land units not necessarily covered by vegetation but constituting porous surface covers and permeable soil structures are also recognised as complementing the green infrastructure concept (*e.g*. Bucht & Persson, 1995; Shuster *et al*., 2011; McPhearson *et al*., 2013; USEPA, 2014). This includes *e.g*. vacant lots and ruderal areas, gravel beds and permeable paving systems and often relates to sustainable drainage systems, urban agriculture, biodiversity *etc*. (Jaffe, 2010; Colasanti *et al*., 2010; Berg *et al*., 2013; Bonthoux *et al*., 2014). Such land cover and land use areas contribute to the green infrastructure in a complementary way, *i.e*. they may not be sufficiently capable of sustaining a multifunctional role themselves, but contribute to ecological function in the overall network of processing certain ecosystem services (Colding, 2007; Day & Dickinson, 2008). This is also highlighted in the work of Bucht and Persson (1995) in conjunction with an enquiry relating to the Planning and Building Act in Sweden (PBL-utredningen, 1994).

3.1.2 Green infrastructure roots – a historical outlook

Green infrastructure as a term or name was conceived in the 1990s in the USA (William, 2012), and most of the literature published on green infrastructure in the beginning of this century is American (Kambites & Owen, 2006). Today, the term green infrastructure is used on both sides of the Atlantic, as well as in countries such as South Africa, China and Australia (*e.g*. Chang *et al*., 2011; Llausàs & Roe, 2012; Schäffler & Swilling, 2013; Kilbane, 2013). However, green infrastructure as a concept *per se* is not a new idea or recent appreciation of the interdependency of urban and rural landscapes, built-up space and green space, or of the 'nature-culture' relationship or ecological and anthropogenic processes. Rather, it is the result of ideas by pioneering individuals and subsequent theories gradually evolving over a given time. The conceptual and theoretical roots which permeate contemporary approaches to green infrastructure are thus an assortment of concepts and rationales from various contributing disciplinary fields (Benedict & McMahon, 2006; Davies *et al*., 2006; Kambites & Owen, 2006).

Within the field of landscape planning and architecture, early perceptions and explicit implementations of what would today be called a green infrastructure approach are usually attributed to Frederick Law Olmsted and his projects in Boston, Riverside, New York *etc*. during the latter half of the 19th century (*e.g*. McDonald *et al*., 2005; Mell & Roe, 2007; Newell *et al*., 2013). Olmsted managed to fuse urgent environmental concerns of his time, *e.g*. pollution, flooding, sewage treatment *etc*., with simultaneous aspirations to create a landscape for recreation and well-being for the urban citizen. Olmsted was a master of bridging scales – in space and in time. With the example of Back Bay Fens in Boston, his detailed concern for species selection, site-level qualities and indigenous landscape processes helped establish a green space system capable of delivering fundamental recreational services whilst adapting to environmental fluctuations such as salt marsh flooding (Martin, 2011). Over 150 years later, Back Bay Fens is still a vital asset of the Emerald Necklace, providing a refuge from the city bustle and alleviation of current and increasing problems of storm water runoff.

Ebenezer Howard's visions of the Garden City in early Twentieth Century Britain could also be seen as a prelude to some of the current discussions on recreational and social amenities linked to the green infrastructure concept (Benedict & McMahon, 2006; Mell & Roe, 2007). Although Howard's ideas of social reform and spatial principles of *e.g*. encircled zoning (subsequently leading the way to the Green Belt policy in the UK) are partially outdated, the concept of green infrastructure still corresponds to Howard's views on context-dependent design and seeing the "magnets of nature [and] society" and "town and country" being merged into one (Howard, 1902). During the Twentieth Century, a number of contributors continued to influence what is currently embraced in the green infrastructure concept – *i.e*. the ideas of greenway planning (*e.g*. MacKaye, 1928), the landscape as a living system and ecological design (*e.g*. Hackett, 1950; Odum, 1953), and the role of social and cultural dynamics for a sustainable urban landscape (*e.g*. Jacobs, 1961; Gehl, 1971).

In 1969, Ian McHarg published the seminal book *Design with Nature*. With collaborative disciplinary integration of meteorology, geology, geomorphology, hydrology, soil science, animal ecology, cultural anthropology *etc*., McHarg dealt with the challenges of environmental planning with interdisciplinary expertise, ultimately resulting in a series of overlays delineating a recapitulation of natural patterns and processes occurring in the landscape. McHarg's plans are systematic and chronological, with a pinpoint focus on the causality of components and actions – whether induced by humans or not (McHarg, 1969). The methodology involves an approach to the landscape as an entity of functions and processes, although the overlays also depict tangible formations of 'landscape' as a perceptive and aesthetic creation. However, McHarg's methodology has been criticised for objectifying the landscape, for its mapping and quantification of components and processes (Reed & Lister, 2014). Further criticism of McHarg's work concerns his misunderstanding of the planning-design relationship and the important role cultural processes play in shaping the landscape (Mossop, 2006). According to Mossop (2006), McHarg contributes to polarisation between 'nature and culture' where human-induced design is subordinate to natural process.

Still, '*Design with Nature*' provided a conceptual basis for our present understanding of green infrastructure in *e.g*. GIS (Geographic Information Systems); as a physical entity and as a methodological approach that is temporally and ephemerally bound yet spatially defined. This has helped to construct a tentative, albeit quantitatively mapped interface to green infrastructure planning in a regional context, and highlights the interaction of urban and rural areas. However, McHarg also draws attention to details of micro-scale components – to why entities are constructed as they are and for what functions. The interactions of pattern and process, but also scale, are thus central to McHarg's work.

In '*The Granite Garden*' by Anne Whiston Spirn (1984), the detail of the pattern-process interactions introduced in '*Design with Nature*' in 1969 is captivatingly developed through documentation of the urban landscape and the role of green structure. The interdependent relationship between nature and humankind, and how natural process and cultural history can guide planning and design of a viable urban landscape, are rendered throughout Spirn's work using a multi-scalar approach. An overarching view of the landscape, of *e.g.* large-scale hydrological systems, is directly linked to site-level design, engineering and management (Spirn, 1984). Thirty years later, current discourses on green infrastructure planning, design and management (*e.g.* Tzoulas *et al.*, 2007; Ignatieva *et al.*, 2013; Rouse & Bunster-Ossa, 2013) still mirror the fundamental ideas so vividly depicted in '*The Granite Garden'*. In furthering our understanding of how green infrastructure planning can better fit with the current challenges of *e.g.* global climate change, spatial patterns of urban growth, human welfare *etc.*, ideas of resilience and social-ecological processes have started to permeate the green infrastructure concept. (The conceptual trajectories of resilience and an ecosystem approach are discussed in sections 3.3 and 3.4 of this thesis).

Although the green infrastructure approach may lack a unified theoretical foundation, it provides a framework from which urban green space can be discussed with regard to relevant needs for environmental and social sustainability (Mell, 2009). According to Hansen and Pauleit (2014), the theoretical framework of ecosystem services may prove beneficial to the green infrastructural approach with regard to both multi-functionality and connectivity. Such a discourse could subsequently help inform practitioners in green infrastructure planning about *e.g.* green infrastructure functions, services and benefits at different spatial levels (Hansen & Pauleit, 2014). As mentioned previously, individual configurations of *e.g.* trees, porous paving and sedums roofs have been shown to contribute to the overall green infrastructure in a number of research papers and government documents (*e.g.* Bucht & Persson, 1995; Shuster *et al.*, 2011; McPhearson *et al.*, 2013; USEPA, 2014). Merging the theoretical foundation of ecosystem services and green infrastructure, as reviewed by Hansen and Pauleit (2014), could further help reveal the function and service of disperse green structure in a broader social-ecological context. Tracing the functions and services needed in a place-specific situation could lead to a clearer definition of which landscape structures or processes are required. One necessary step in this direction would be to align the green infrastructure terms of landscape function, service and benefit to the corresponding terms of functions and capabilities used in the ecosystem discourse (Haines-Young &

Potschin, 2010), as the green infrastructure differentiation between landscape function and service is somewhat indistinct today (Hansen & Pauleit, 2014).

3.2 The related field of landscape ecology

The interplay of spatial-temporal patterns in the landscape makes up a central core in the field of *landscape ecology* (Forman & Godron, 1986; Turner *et al*., 2001). In contrast to McHarg's approach, landscape ecology projects from a metric system and a "template" which makes up the patch-corridor-matrix model for assessing spatial heterogeneity (Urban *et al*., 1987; Sarlöv-Herlin, 1999; Uuemaa *et al*., 2009). Landscape ecology often deals with land-mosaic theory (Dramstad *et al*., 1996; Forman, 2008). It contains three comprehensive characteristics: 1) structure (spatial or land-use pattern), 2) function (movement and flow of components), and 3) change (the dynamic and metamorphosis of patterns) (Turner, 1989; Forman, 2008). The structural pattern (characteristic 1) consists of patches, corridors and matrix, where patches make up non-linear surface areas (usually assemblages of plant and animal communities, but not always), corridors are linear formations (for transportation, flows, windbreaks *etc*.), and the matrix is the homogeneous mass in which the patches and corridors are embedded (Forman & Godron, 1986). The physical arrangement of the patch-corridor-matrix model shares much similarity with the green infrastructure ideal of hubs, links and sites (Figure 9).

In several studies of landscape ecology, the built-up urban landscape (of buildings and grey infrastructure) is often referred to as the 'built matrix' (*e.g*. Lovell & Taylor, 2013) or the 'urban matrix' (*e.g*. Hess *et al*., 2014; Johnson & Swan, 2014). Patches are often identified as comprising *e.g*. parks, recreation grounds, cemeteries, vacant lots, schoolyards, residential gardens *etc*. (*e.g*. Goddard *et al*., 2009; Lovell & Taylor, 2013). Corridors may consist of rivers, streams, linear parks, planted railroad tracks, road verges *etc*. (*e.g*. Ahern, 1999; Coffin, 2007). How the aggregative pattern and potential process of individual fine-scale green structure fit into the patch-corridor-matrix model is somewhat unclear, however. A major reason for this may be that the landscape ecology model has foremost been applied with focus on the variation and dispersal of different species groups, where seemingly fragmented and individual green elements would provide poor structural connectivity (Antrop, 2001; Breuste *et al*., 2008). The matrix is often portrayed as a "sea of greater or lesser hostility" with varying degrees of inhabitability (Haila, 2002; Baudry *et al*., 2003; Manning *et al*., 2009), and attention becomes directed towards increasing the conservation and connectivity between patches (Baudry *et al.*, 2003; Lovell & Johnston, 2009).

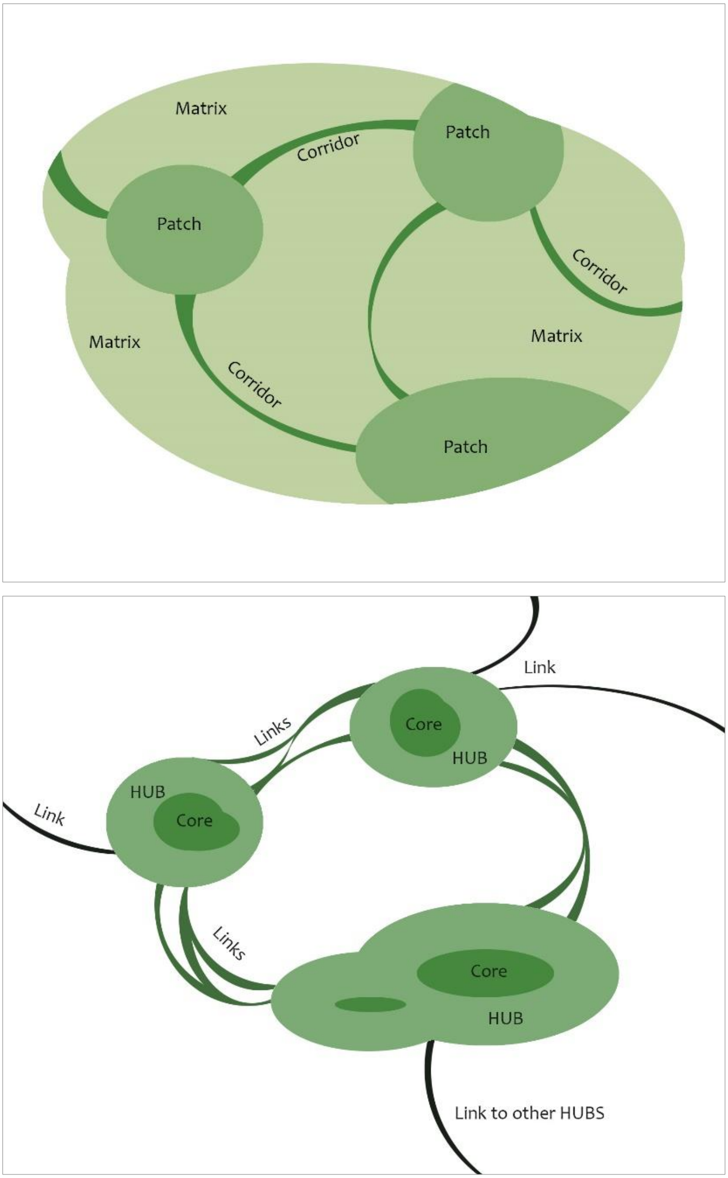


Figure 9. Conceptual illustrations of the physical arrangement of the patch-corridor-matrix model as illustrated in landscape ecology (top) and the green infrastructure model of hubs, cores and links (bottom).

However, structural corridors and patches do not always support functional connectivity for other organisms (Donald & Evans, 2006; Lindenmayer & Fischer, 2006; Boitani *et al.*, 2007). Several studies based on research in rural landscapes have found that in some situations, the matrix, depending on its structure and quality, may indeed play an important role for *e.g.* foraging, breeding and increased immigration for a number of animal species (Kupfer *et al.*, 2006). According to Verbeylen *et al.* (2003), Revilla *et al.* (2004) and Andersson (2006), the matrix is rarely homogeneous. In urban contexts this is even more true. As a result, consensus is growing on recognising the matrix as a resource and acknowledging that landscape function and resilience may indeed be improved by *e.g.* increasing the quality of the matrix and developing spatial heterogeneity (Fischer *et al.*, 2006; Vandermeer & Lin, 2008).

In a review by Lovell and Johnston (2009), improving the multi-functionality of the urban matrix is analysed with emphasis on fine-scale green structure elements such as swales, raingardens and shade planting in *e.g.* residential gardens. Although – as Lovell and Johnston (2009) admit – these individual elements "might not appear to have a large impact on the environment, [their] contribution could be significant when considered together within the entire landscape and if they are intentionally designed to improve landscape performance". While studies often refer to the potential of the green structure embedded in the urban matrix (*e.g.* Goddard *et al.*, 2009; Lovell & Taylor, 2013; Turrini & Knop, 2015) a term or concept describing the collective pattern of scattered fine-scale green structure is still lacking. In Lovell and Taylor (2013: p. 1449), with reference to Goddard *et al.* (2009), "small fragmented patches" are mentioned to describe *e.g.* residential gardens, cemeteries, vacant lots and "other interstitial spaces". In Jim and Chen (2003: p. 95), urban green space is taken to comprise "semi-natural areas, managed parks and gardens, supplemented by scattered vegetated pockets associated with roads and incidental locations". With a focus on structural connectivity, individual trees and small green spaces at the neighbourhood scale are configured to make up linear elements (green corridors) in the Jim and Chen (2003) study, which those authors refer to the "greenspace matrix". This corresponds to a certain degree with Gill *et al.* (2007), who in order to define and physically conceptualise dispersed green structure propose a break-up of the green infrastructure concept itself into corridors, patches and matrix. What is referred to as dispersed green structure in this thesis is therefore consistent with green matrix (Gill *et al.*, 2007).

In conclusion, the question of how to 'fit' disperse green structure into the landscape ecology approach has much to do with the spatial scale and focus of the analytical 'lens' used. As Jax (2007) explains, ecosystems are not defined to a strict spatial dimension. However, Corry and Nassauer (2005) point out that the metrics of *e.g.* perimeter-to-area ratio, mean patch size and other empirical indices often used in the field of landscape ecology may be more valid for comparing different landscapes and configurations at coarse scale (low resolution). In fragmented landscapes with high resolution data, Corry and Nassauer (2005) conclude that applying such pattern indices for comparing ecological functions for fine-scale configurations (and habitats) is of rather limited use. How to employ the metric system of landscape ecology to appraise the landscape function of disperse green structure in *e.g.* densely built-up urban areas is – based on the general and broad review presented here – quite ambiguous.

3.3 The ecosystem approach

The concept of an ecosystem approach captures in broad terms the holistic view of interconnectedness between humans and other living beings and the surrounding environment. As Willis (1997) more eloquently puts it "[ecosystems are]… communities of organisms and their physical and chemical environment and the continuous fluxes of matter and energy in an interactive open system". The ecosystem approach is a concept that has been prominent in many of the world's religions for millennia (Capra, 1997), but progressed mainly in the Western world during the Twentieth Century and more recently gained impetus through the Millennium Ecosystem Assessment (UN, 2005).

The term *ecosystem* was initially coined by the British plant ecologists Roy Clapham and Arthur Tansley in the 1930s and emerged from studies and scientific discussions with fellow scholars in the field of successional patterns in plant communities (notably Frederic Clements and Henry Gleason) (Raffaelli & Frid, 2010). However, segregating discussions of a natural scientific discourse and of humanities and creating a schism between reductionist and holistic approaches have characterised the research community of ecosystem science throughout the Twentieth Century (Waltner-Toews *et al.*, 2008). A further concern has been that the ecosystem concept is too loose a terminology, efficiently transferred to various purposes and as Raffaelli and Frid (2010) expressively put it: an "all-things-to-all-people" concept. However, this is gradually subsiding due to the efforts at combining rigorous environmental and social science through the initiatives of the Millennium Ecosystem Assessment

(UN, 2005) and the forerunner programme of the Ecosystems Approach (UN, 1992).

Today, the ongoing and unsustainable relationship between human activity and natural resources has led to a growing research discourse on ecosystems and human communities. With a worldwide increase in urban populations, scientific studies of urban ecosystems are inevitably emerging. Ten years ago, Alberti (2005) acknowledged that research on urban ecosystems needs to recognise the complexity of the urban landscape as not comprising of one system, but several interlinked *subsystems*. During the same period, Turner pointed out the limited focus of ecosystem ecology within the field of landscape ecology and claimed that the potential marriage of both discourses may shed additional light and provide an integrated understanding of landscape functions (Turner, 2005). The call for further appreciation of socio-ecological processes in relation to alternative land use and spatial patterns should thus be prominent in urban ecosystem research according to Schewenius et al. (2014). These proposals clearly encourage new perspectives. In terms of green infrastructure and dispersed green structure, they seek alternative approaches to spatial and temporal relationships. The green infrastructure network does not comprise one unified system, but is a multi-layered network encompassing several subsystems. Space and spatial patterns could also fit into this sub-system approach – encouraging alternative routes to relate vertical and horizontal structures and spatial patterns occurring above and below surface level. As such, each subsystem in turn needs to be re-viewed with regard to spatial make-up and context, human activity and requirements, and the ecosystem services that green structures may provide today and in the future.

3.3.1 Ecosystem services for green infrastructure planning

Ecosystem services stem from the function or capacity of landscape structures or processes (Haines-Young & Potschin, 2010), and are allocated into different categories of supporting, regulating, provisioning and cultural services (TEEB, 2014) (Figure 10). These have in common context dependency and subsequent links to people’s needs (Banzhaf & Boyd, 2005; deGroot *et al.*, 2010). However, people themselves, their values and perceptions affect landscape structures, processes and functions (Nassauer, 1995b) and this in turn indicates an interdependent but vulnerable relationship between structure, ecological resource, service and living beings. Applying such a systems approach to *e.g.* green infrastructure planning would, according to Mell (2009), help encourage equal flows into and out of the green infrastructure system, *i.e.* support the resource of green infrastructure whilst allowing for human needs. Integrating the role of ecosystem services and linking an ecosystem approach to *e.g.* green infrastructure planning can thus help support an anthropocentric framing rather than a solely ecocentric approach of system values. According to Palmer *et al.* (2004), research agendas centred on ecosystem services help establish a common ground for communication between practitioners and scholars. A study by Hansen *et al.* (2015) further illustrates that human well-being and how humans in particular benefit from ecosystem services are frequently cited in a number of planning documents in both European and North American cities. The same study showed that although “habitat for species” and “recreational values” were amongst the most recognised and sought-after services, “runoff mitigation” and “local climate regulation” were much appreciated (Hansen *et al.*, 2015). The link between regulating ecosystem services and human well-being could therefore be discussed in light of how to expose the function and process of disperse green structure in the urban landscape.

Although not necessarily using the term ‘regulating ecosystem services’, a number of such research studies have been conducted in fields concerning urban green structure during recent decades. These studies entail both site-level studies of *e.g.* individual trees and rainfall interception, permeable surface and rainfall infiltration/water quality and the effects of trees on building energy use (see *e.g.* Xiao *et al.*, 2000; Brattebo & Booth, 2003; Nikoofard *et al.*, 2011), or studies of larger geographical contexts highlighting the role of vegetation and green infrastructure for precipitation events, energy exchange, urban cooling and the mitigation of urban heat island effects (see *e.g.* Florgård & Palm, 1980; McPherson *et al.*, 1997; Eliasson & Upmanis, 2000; Gill *et al.*, 2007). These studies give a good indication of the capacity and performance of green structure with regard to expected services and benefits – assuming that the structures are in adequate condition to function. Knowing how the function in turn relates to spatial and temporal fluctuations and the influence of social-ecological processes would further deepen our understanding of green infrastructure resilience and how the green structure in the urban landscape adapts to change.

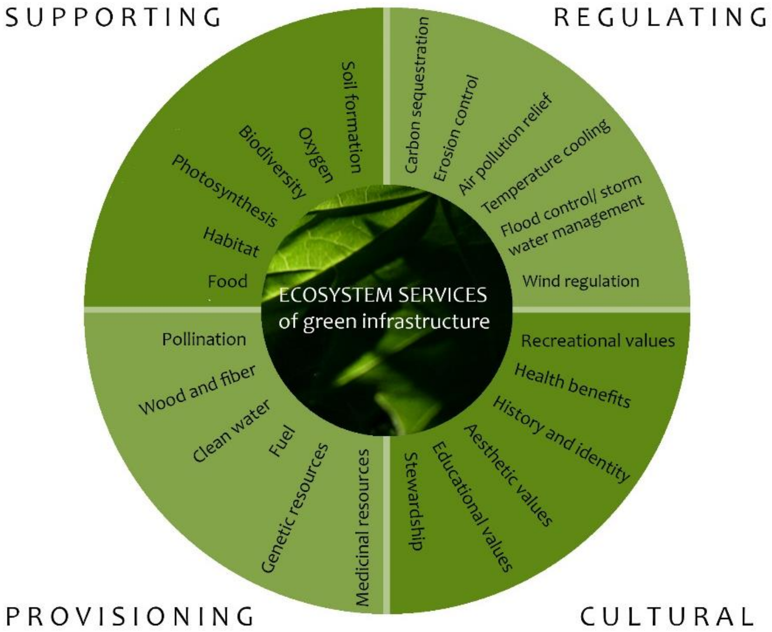


Figure 10. Ecosystem services can be divided into the categories of supporting, regulating, provisioning and cultural ecosystem services. The above illustration depicts some examples of the ecosystem services provided by green infrastructure, (adapted from the TEEB (2014) categorization).

3.4 Resilience studies

Resilience, in its well-accepted definition, is to accept change and embrace unpredictability with the certain notion that the system concerned will reorganise and rebound to a similar arrangement – hopefully with improved qualities (Folke *et al*., 2002). Irrespective of system, whether a tree, a woodland or a city, it will not stay at a long-term equilibrium or stable state no matter how much effort is put into various maintenance strategies. In fact, any endeavour aimed at maintaining an optimised state of "culmination" will consecutively increase the system's vulnerability to external perturbation (Raffaelli & Frid, 2010).

However, after decay, disintegration or collapse – or what Gunderson and Holling (2002) describe as "creative destruction" – the remaining capital of the system will be released and it will subsequently self-organise to a novel system. Depending on the resilience of the initial system, the new system might not rebound to its original characteristics, but rather bounce "forward" to an adaptive state (subject to yet another passing of ephemeral equilibrium) (Adger, 2003). This is what Holling (1973) refers to as *ecological resilience*. An illustrative example of this is the successional development of a forest environment: the sequence of pioneer species and subsequent climax species, developing into a stand and later a forest, the creative destruction of *e.g.* a fire or an outbreak of pest and disease, and the following regeneration of new species, a new succession, a new collapse, and so on. There is no "end-state", but still an underlying belief in the existence of some kind of balance, or that the system will hark back to a comparable arrangement (Frid & Raffaelli, 2010).

According to Frid and Raffaelli (2010), the 'balance of nature' perspective is nonetheless a simple one and often does not consider the equilibria of other configurations within the system. With regard to landscapes, individual adaptive cycles (*i.e.* configurations) within the social-ecological system rather create a 'panarchy' (non-hierarchical organisation of multiple scale of space, time and social organisation) (Gunderson & Holling, 2002). In this panarchical system numerous equilibria occur while it is subjected to either long-term change or rapid transformation (Selman, 2012). In sustainable urban development, the belief in a progression towards one true equilibrium may mislead and misdirect the planning discourse. It can easily create a belief that the making of a resilient urban landscape involves measures and a discourse that will encourage structures and processes to rebound to their former functions after experiencing shock or disturbance. It inevitably stimulates a 'tunnel vision' approach to planning and discourages the more troublesome question of: What if it doesn't go back to the seemingly 'normal'? Davoudi (2012) advocates what she calls *evolutionary resilience*. This does not support the necessary rebound to a state of equilibrium; instead it underpins non-equilibria and the transformation of systems. Hill (2005: p. 143) further defines it as a "meta-stable" set of conditions that "constantly disappears and reappears". A similar idea is proposed by Folke *et al.* (2010), who use *transformability* as a concept to describe a system's "capacity to cross thresholds" into new scenarios. This in turn creates alternative trajectories for urban development and, not least, for green infrastructure and dispersed green structure planning. It provides a palette of alternative options and prompts unconventional approaches. It also motivates questions on preconceptions of the future and possible outcomes among those planning, designing and maintaining the urban landscape using measures based on present values. In evolutionary resilience thinking, experience and the continuum of knowledge is central and thus, as Ahern (2011) articulately explains, planning the sustainable future does not entail "fail-safe" solutions, but experimentation and design that are "safe-to-fail". Sustainable development and resilient planning is thus a continuous process where learning and experience lie at the heart and where "optimum solutions" to future uncertainty are not based on present principles or indices tied to static values, but rather an inbuilt flexibility for a variety of outcomes.

Another important aspect of resilience theory is the understanding of feedback loops. These occur either in a positive or negative sense. Positive feedback reinforces subsequent behaviours (of a given situation) until one side dominates, whilst negative feedback modifies behaviours (Berkes *et al*., 2003; Alberti & Marzluff, 2004). The use of air conditioning in buildings is an example of a positive feedback loop, where the cooling of buildings and cars to alleviate thermal stress from increasing temperatures in turn increases the magnitude of greenhouse gas emissions – which in turn subsequently push climate change and even warmer temperatures. Negative feedback loops allow for different routes to occur and for the system to find alternative ways around a situation (Kay, 2008). In the urban landscape, green infrastructure may help provide such negative feedback. Depending on local conditions and qualities (in the materialistic sense and as regards cultural and biological interactions), green infrastructure has the potential to support a diversity of functions – functions that are themselves contingent on a diversity of structures and interactions (*e.g*. Bennet *et al*., 2005; Lister, 2008). The negative feedback loops of green infrastructure systems are thus linked to *diversity* and *connectivity*; diversity in their very make-up, *i.e*. biological diversity and architectural composition, and connectivity above and below surface level. The connectivity may be visually hidden, but is still dependent on biological and cultural input (management) and on how space and spatial patterns are viewed (Cumming, 2011).

With its focus on disperse green structure in built-up urban areas, evolutionary resilience thus encourages a re-viewing of the relationship of space and structure in the urban landscape to landscape function and consequent services. Similar parallels of operative and efficient urban space with regard to spatial patterns and densification strategies have been drawn by Ståhle (2005). However, change may not only occur due to external disturbance, but may just as easily arise from within the system (Bolliger *et al*., 2003; Reed & Lister, 2014). External forces of climate, weather, population growth, spread of pests and disease *etc*. are met with internal pressures due to *e.g.* short-sighted building practice and use of materials, daily habits and misdirected preconceptions. Moreover, disturbance and collapse do not necessarily occur as and where expected. This emphasises why resilience should be encouraged *throughout* the urban landscape and within built-up areas, and not only in pre-defined zones and locations. Dispersed green structure may thus provide important nodes and processes for self-organisation. Dispersed green structure exemplifies what Levin (1998) and Naveh (2000) highlight as important qualities to sustainability and resilience; the role of sub-systems and the interaction at local levels. It further hints at the idea of chaos and the butterfly effect – where even the smallest component and process can bring about larger-scale change and contribute decisively to future directions (Lorenz, 1963; Stewart, 1989; Kauffman, 1993; Selman, 2012).

3.5 The related field of urban ecology

The last conceptual approach to be reviewed here with regard to its applicability to the study of dispersed green structure and subsequent functions and services is urban ecology. Urban ecology could be seen as an amalgamation of the study of social-ecological systems, resilience and ecosystem studies, and the disciplinary field of landscape ecology where the urban environment and landscape lie at the heart (Niemelä, 2011). It has a strong focus on planning and decision-making and how knowledge of the social-ecological interactions in the urban landscape can help guide future urban sustainability (*e.g.* Niemelä, 1999; Alberti *et al.*, 2001; Steiner, 2014). McDonnell (2011: p. 9) gives the following definition of urban ecology: “Urban ecology integrates both basic (*i.e.* fundamental) and applied (*i.e.* problem oriented), natural and social science research to explore and elucidate the multiple dimensions of urban ecosystems”. This standpoint helps explain why urban ecology has evolved into an interdisciplinary and transdisciplinary science (Alberti, 2008), and why the anthropocentric perspective has gradually become an accepted, albeit much discussed, approach in the study of urban ecosystems (Young & Wolf, 2007; Dooling *et al.*, 2007).

A brief and comprehensive review of the history of urban ecology reveals how it was originally influenced by the Chicago school of sociology/human ecology in the USA (a collaboration of scholars in urban sociology) (Axelrod, 1956). Although the field experienced a surge of innovative development from both ecologists and sociologists in the 1920s to the outbreak of the Second World

War, it was not until the mid- to late Twentieth Century that urban ecology emerged as the social-ecological science we know today (McDonnell, 2011). According to *e.g*. Douglas *et al*. (2011), an influential reason was the increased awareness and recognition of the human-induced impact on ecosystems in the 1960s and 1970s. Theories of temporal and spatial variation and its implications for ecological studies also created a heterogeneous and non-deterministic attitude in ecological science (Wiens, 2000). The launch of the Man and Biosphere Programme (MAB) in 1971 helped establish further acceptance of the social-ecological approach, with the first intergovernmental and international research project in urban ecology (Breuste *et al*., 1998). The MAB Programme can be seen as the first initiative to encourage interdisciplinary considerations in the science of ecology, unifying the fields of natural sciences, planning/engineering and humanities (Celecia, 1991; McDonnell, 2011). Today, as a result of the early engagement in the 1970s to the beginning of the Twenty-First Century, urban ecology covers the broad scientific scope of ecology *in* and *of* urban landscapes (*i.e*. studies of the non-human organisms in urban environments and studies of the urban landscape as an ecosystem), and of ecology of urbanisation gradients and the sustainability of cities (Douglas & Ravetz, 2011; Wu, 2014). In addition, Wu (2014) points out that the attention to ecosystem services and their subsequent benefits for human well-being is increasingly playing a role in the future direction of urban ecology science. The non-deterministic concepts of non-linearity and non-equilibria are also considered important influences for current and future trajectories in urban ecology, where *e.g*. succession and sustainable design rely on both environmental and historical context (Alberti, 2003).

McDonnell (2011) pointed out how most studies in urban ecology concern the ecology *in* urban landscapes, *e.g*. small-scale studies located within the city and carried out in a distinct disciplinary approach. Consequently, it is possible to find many studies on the performance of *e.g.* sedum roofs and biodiversity (Tonietto *et al.*, 2011; Madre *et al*., 2013), and of street trees and different ecosystem services and community benefits (Heisler, 1986; Nagendra & Gopal, 2010; Jack-Scott *et al*., 2013) under the umbrella of urban ecology. Papers I-IV in this thesis conform largely to this category in urban ecology, *i.e*. individual studies of an ecological process *in* an urban landscape.

Studies concerning the ecology *of* the urban landscape, on the other hand, are employed in order to gain a broader viewpoint on the spatial-temporal relationship of vegetation, surface covers and buildings. Similarly to the field of landscape ecology, the concept of a pattern-process approach that considers both human-induced and natural system dynamics (*e.g.* Sukopp, 1998; Weng, 2007; Pickett & Cadenasso 2008) is applied to illustrate this perspective. The approach often uses or even contributes to different classification systems linking land use and land cover to ecological, social and economic processes (Zhou *et al.*, 2006; Mathieu *et al.*, 2007). However, Cadenasso *et al.* (2007) emphasise that studies relying on land use classifications based only on biotic components or projected at coarse-scale resolutions (1 km) increase the likelihood of overlooking the finer-scale heterogeneity of urban areas. Not only do overly coarse-scale classification systems separate human and natural components, but they also ignore the variety of *e.g.* vegetation and surface materials, and the "joint role of human agency and vegetation processes in urban mosaics" (Pickett & Cadenasso, 2008: p. 9).

With regard to disperse green structure, urban ecology provides an enabling backdrop for concepts and theoretical relations to *e.g.* landscape ecology, resilience and complex systems thinking. Although individual site-level studies make up a well-presented volume within the field, a challenge in urban ecology lies in linking site-level configurations and the effects of small-scale change to a wider planning perspective and to studies of ecology of urban landscapes (Cadenasso *et al.*, 2007). Cadenasso *et al.* (2007) further emphasise the need for quantifying the fine-scale heterogeneity of natural and built components, where *e.g.* the interdependency and localised feedback of site-level green structure can be further revealed, with tangible benefits to society (Tanner *et al.*, 2014).

3.6 Concluding reflections

How the role of disperse green structure is recognised in the conceptual approaches discussed above seems to relate to whether and how human benefits are identified (*i.e.* how people can gain from green infrastructure) and how different components (irrespective of size) can be seen as making up interconnected systems at different scalar and temporal levels (*e.g.* in resilience studies, urban ecology and the ecosystem approach). As mentioned in the introduction to this chapter, the concepts of green infrastructure, landscape ecology, ecosystem services, urban ecology and resilience are closely intermingled and in some cases it may even be unnecessary to try and separate them. In the field of green infrastructure – as a conceptual phrase and planning approach – elements of individual green structure are widely recognised and this is further mirrored in the fields of urban ecology and in studies concerned with urban ecosystems and ecosystem services.

In this thesis, urban ecology, resilience studies and the green infrastructure approach are used to help justify why even fine-scale elements and configurations are appropriate subjects to investigate for sustainable landscape development. Although it was difficult to fully relate the work of this thesis to the metrics often used in landscape ecology methods, the conceptual approach of Paper I was derived from theories on spatial-temporal relations first described by Antrop (2005) for landscape ecology. In order to explore how the historical landscape of hydrological structures in the urban core of Lund influences current approaches to sustainable drainage systems and its integral role in urban-rural landscape functions, the conceptual approach of green infrastructure, urban ecology and resilience studies was applied as described in Paper I (*e.g.* Antrop, 2000; Gill *et al*., 2007).

For all studies presented in this thesis, the ideas of green infrastructure and urban ecology were conceptually relevant and fitting, as they recognise multi-scalar processes and include studies focusing particularly on the role of individual configurations of green structure (*i.e.* trees, lawn, porous paving, sedums roofs *etc*.) and their role for landscape function (*e.g.* Spirn, 1984; Bucht & Persson, 1995; Gill *et al*., 2007; Cadenasso *et al*., 2007; McPhearson *et al.*, 2013). The ecosystem approach and resilience studies, in their acknowledgment of multi-layered networks and function diversity, create an incentive to increase understanding and knowledge of how fine-scale configurations (in this case disperse green structure) constitute necessary elements in broader contexts (here landscape function) (Lister, 2008). This helped in the argument and aim of this thesis to produce tangible indices on the contributions of fine-scale green structure to regulating ecosystem services.

4 Delimitations

The reviews in parts of the preceding chapter of disperse green structure comprising interlinked subsystems (*e.g.* Alberti, 2005) can facilitate a rather interesting approach in establishing network-based analyses of disperse green structure from a social-ecological perspective. Such an approach was not applied to this thesis, however. Instead, dispersed green structures and regulating ecosystem services of stormwater mitigation, wind regulation and mean radiant temperature modification were examined in separate studies to shed light on how different green structures modulate regulating ecosystem services and how site-specific complexities influence this capacity. The studies thus highlight the *potential* of dispersed green structures (through their role of regulating ecosystem services) for future research and discussion, where further steps towards different network analyses can be made.

There are also a number of evaluation tools such as the Green Space Ratio (Kazmierczak, & Carter, 2010), the Sustainable Sites Initiative (SSI, 2009), the i-Tree tool (USDA Forest Service, 2014), the evaluation systems of *e.g.* LEED and BREEAM (USGBC, 2014; BREEAM, 2014) and the Swedish Miljöprogram SYD (Miljöprogram SYD, 2009) *etc.*, which are practice-orientated models aiming to quantify green and spatial structure and subsequent potential to provide various benefits. Reference to these assessment programmes was made to locate the quantitative approach in this thesis in a contemporary context with regard to the planning and building process – primarily in Sweden but also internationally. However, the aim was not to compare, review or give a detailed criticism of these programmes.

The specific economic benefits of regulating ecosystem services of green structures are not studied or reviewed in detail (*e.g.* reduced energy use in buildings and subsequent alleviation of financial costs, the economic relief in healthcare costs from reduced thermal stress and consequent effects on illness or mortality, and decreasing financial liability of municipalities and private landowners due to less surface runoff and pluvial flooding). Although these benefits are introduced in this thesis essay and in Papers II-IV, no attempts are made to correlate the results to specific monetary values.

The studies presented in Papers II-IV are based on computer modelling to obtain numerical and tangible values of how dispersed green structure contributes in terms of regulating ecosystem services. However, it was beyond the scope of this thesis to analyse computational modelling or the models used, with details of the algorithms and equations employed to capture the behaviour of the systems being modelled.

Finally, fine-scale elements of green structure embrace a wide-ranging scope of different kinds of vegetation, surface materials and sub-surface constructions, *e.g*. trees, shrubs, herbaceous plants, green sedum roofs, vegetated walls, permeable concrete pavers, porous asphalt, permeable clay brick pavers, grass pavers, structural soil, open graded sub-base, *etc*. In Papers I-IV (on which this thesis essay is based), the type of green structure discussed is governed by available input data used in the computational modelling. Although it would have been of great interest to explore green walls and sedum roofs and their influence on microclimate regulation in this thesis, available input parameters at the time for *e.g*. ENVI-met did not allow these elements to be analysed.

5 Research methodology

5.1 A comprehensive overview of a mixed methods approach

Each of the different studies in Papers I-IV used different research methods. The work was characterised by the use of mixed methods, quantitative approaches and qualitative analyses and discussions relating to urban development (Sandelowski, 2000; Johnson & Onwuegbuzie, 2004). The initial study, presented in Paper I, was carried out during a six-month research trainee assignment at SLU. In its methodological approach and use of concepts, it represents an “embryonic exploration” of the present research topic. The following three studies, presented in Papers II, III and IV, were conducted to compute tangible values of dispersed green structures – concrete and numerical values inspired by the work in Paper I. Papers I and II share the geographical urban context, namely the Höjeå river catchment, Sweden. This is also true of Paper III to some extent, since the focus was still on the effects of urbanisation occurring in the same geographical area, although specifically in Lomma Harbour. The final study (Paper IV), which is a spinoff from the work presented in Paper III, is not explicitly located in Lomma Harbour, but describes a fictional study site representative of a small public square along the geographical area of the Swedish Öresund coast.

The *case study* concept was used in all four studies and was based on the definition by Johansson (2003) that a case should be: 1) a complex functioning unit, 2) investigated in its natural context with a multitude of methods, and 3) contemporary. The thesis work comprised both inductive approaches (Paper I) and deductive methods (Papers II-IV) (Overton, 1990). According to Persson and Sahlin (2013), one major difference between inductive and deductive reasoning is its applicability to answer the question *why*. Although the inductive approach may be able to discuss the *why* question in terms of a broader generalisation (which will support the probability of ‘truth’ being uncovered), deductive inference helps search for underlying mechanisms (Copi *et al*., 2007). In Paper I, information and data from various sources were compiled to shed light on the spatial patterns of indigenous water structures in the urban core of Lund and how these in turn may hypothetically inform current storm water planning in alternative measures to sustainable development. However, for the studies in Papers II-IV, clear aims and hypotheses were formulated to investigate not only *how* but also *why* dispersed green structure can contribute to sustainable development approaches with regard to regulating ecosystem services. The methods in these studies followed a top-bottom approach and were applied to how the fine detail of *e.g.* spatial relations or species characteristics could feed back to the main hypothesis.

5.2 The modelling process

A substantial part of the thesis was based using computer-based modelling as the method. The computational models of the SCS-CN approach (NRCS, 1986) and ENVI-met (Bruse, 2009) were chosen since they were considered to meet the research aims and questions. The models were also chosen as they might be appropriate to use in practice for landscape planning purposes. The use of the SCS-CN method (Paper II) and the ENVI-met software (Papers III and IV) was not a straight-forward process, but rather an iterative procedure where *e.g.* initial and default input data had to be re-constructed. Therefore, additional input data was used in both cases to either complement (SCS-CN) or replace (ENVI-met) default data. According to Maxwell (1992), the validity of research using *e.g.* computer-based models relies heavily on the input data being accurate. An extensive part of the modelling process was thus to iteratively compare any additionally retrieved data (in the field or through desk study) with similar approaches and results from different research studies (as presented in scientific publications), and to discuss assigned equations with fellow researchers in urban climatology and hydrology. A more detailed account of the modelling process is provided in sections 6.2, 6.3 and 6.4 of this thesis.

6 Papers I-IV – methods and summary of results

6.1 Paper I

6.1.1 Desk study methods

Paper I is a perspective essay based on desk studies of archive studies of historical records, map studies, technical documents, local policy documents and EU and European Commission policy documents. The chief aim of Paper I was to introduce a way of recognising landscape structures of the past and how these in turn may stimulate landscape literacy in future approaches in landscape planning – in this case concerning climate change adaptation and sustainable drainage systems in the urban core of Lund, Sweden. A critical and analytical approach was adopted to explore how the pattern of indigenous water structures has interlaced the urban landscape throughout history, and whether the indigenous water structures of historical Lund are recognised in current storm water planning (see research questions, Chapter 2). In Paper I, indigenous water structure was addressed as blue infrastructure. In retrospect, it should have been referred to as green infrastructure, as done in this cover essay, as this concept entails both water bodies and configurations of vegetation and permeable cover (elements included in the study). However, in the following sections of this chapter, elements of indigenous blue structure and green structure are referred to, in order to maintain consistency with the text in Paper I.

Lund is one of the oldest cities in Sweden, founded in AD 990, and the central built-up area is still much the same in its spatial layout of a medieval pattern with densely juxtaposed buildings and a meandering streetscape (Figure 11). The *case* in this case study was the indigenous blue and green structures of Lund. These blue and green structures represent what Johansson (2003) describes as *physical artefacts* – and in this study they represented 'processes' as much as feature-like elements. Johansson (2003: p. 5) explains how the "artefact is a carrier of its history" and, although not physically present in the contemporary urban landscape, the indigenous blue and green structures are not "dead" but rather make up "non-linear" constructs. In planning research, studies embracing physical artefacts "become more or less historical case studies" (Johansson, 2003: p. 5).

The methodological approach consisted of an iterative process of arranging overlays made up of literature and maps (historical records, technical and policy documents) and information from personal communications (phone calls and emails to professionals within the technical and planning departments at Lund municipality). The initial step was to collect maps and documents which could shed light on past green and blue structures and these were mainly retrieved from the archives of the museum Kulturen in Lund. Subsequent steps consisted of data collection and could be categorised into three themes, relating to landscape, practice and climate (and weather). The illustration in Figure 12 aims to depict the arrangement and methodological process of the study in its entirety.

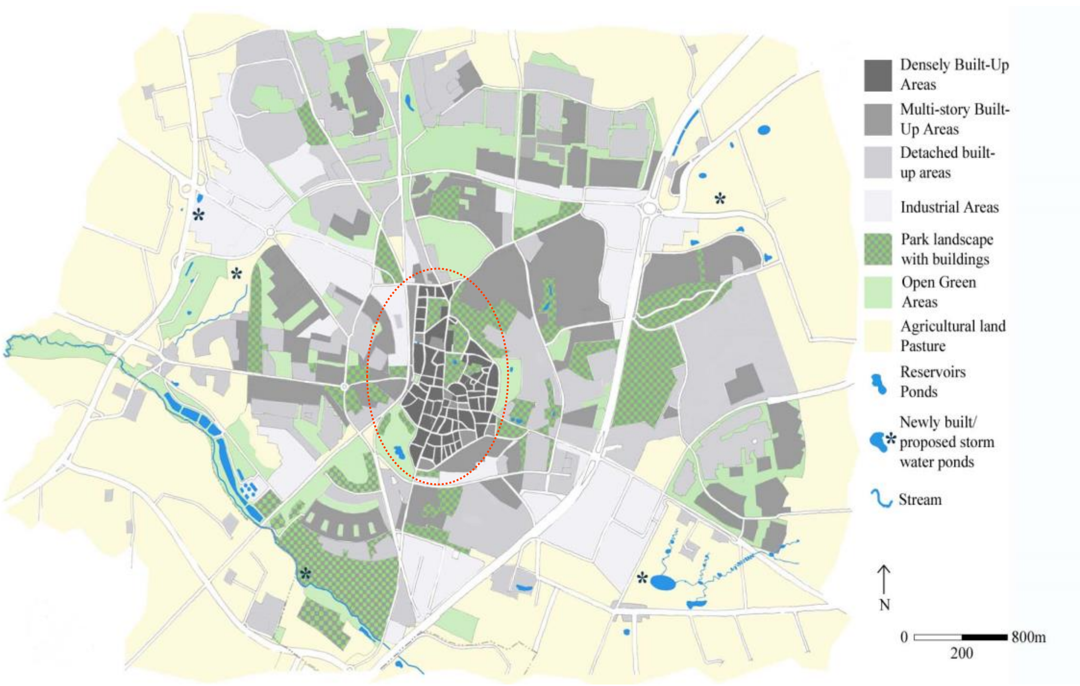
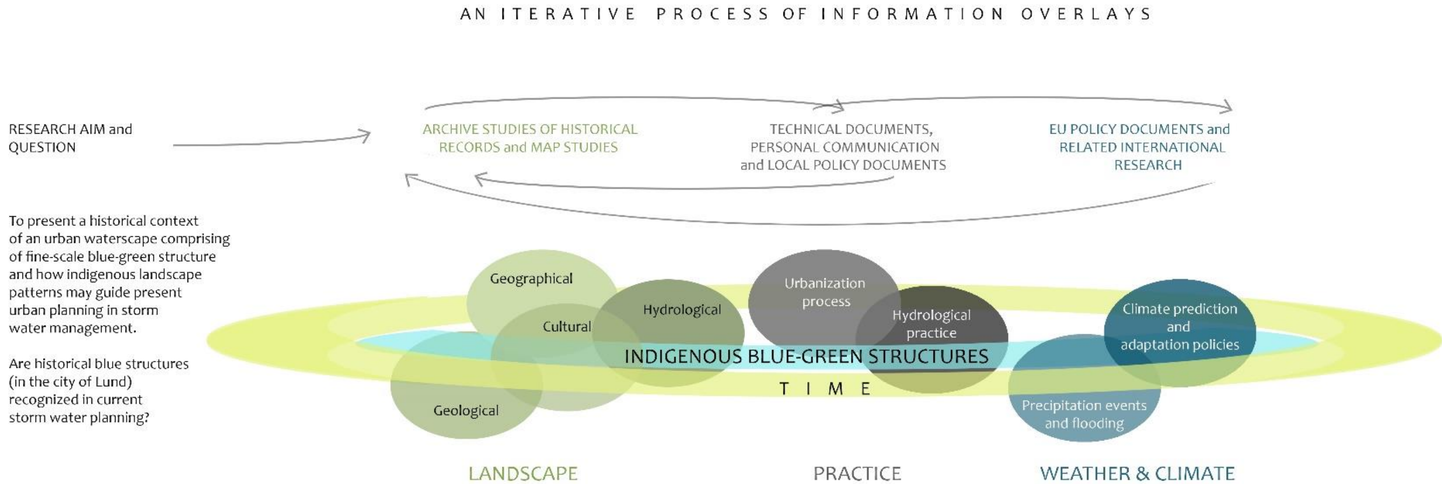


Figure 11. The map illustrates the different land covers in Lund according to the official classification map. The medieval city centre, case study area for Paper I, is encircled.

Figure 12 (next page). Conceptual diagram of the arrangement and methodological process of Paper I.


AN ITERATIVE PROCESS OF INFORMATION OVERLAYS
RESEARCH AIM and QUESTION
To present a historical context of an urban waterscape comprising of fine-scale blue-green structure and how indigenous landscape patterns may guide present urban planning in storm water management.
Are historical blue structures (in the city of Lund) recognized in current storm water planning?
ARCHIVE STUDIES OF HISTORICAL RECORDS and MAP STUDIES
TECHNICAL DOCUMENTS, PERSONAL COMMUNICATION and LOCAL POLICY DOCUMENTS
EU POLICY DOCUMENTS and RELATED INTERNATIONAL RESEARCH
Geographical
Cultural
Hydrological
Geological
Urbanization process
Hydrological practice
Climate prediction and adaptation policies
Precipitation events and flooding
INDIGENOUS BLUE-GREEN STRUCTURES
TIME
LANDSCAPE
PRACTICE
WEATHER & CLIMATE

6.1.2 Final conclusions

Paper I showed how the urban area of Lund has proceeded from a landscape with an extensive hydrological terrain to an impermeable platform set in a catchment area dependent on a hydrological landscape system in interplay between city and its rural surroundings (Figure 13). In terms of actual implementation in a densely built-up cityscape, indigenous green and blue structures in the urban core (of Lund) may help to envision an integrated spatial layout of sustainable drainage systems (SuDS) – a concept seen as impossible according to current planning policies, where SuDS solutions are instead allocated the urban periphery as ponds and detention basins on a larger scale (Lunds kommun, 2010). A further finding was that although Lund is a city carrying on an appreciable historic legacy, knowledge of past hydrological structures – natural or artificial – is absent and unfamiliar to the present planning authorities. By recognising the landscape by its indigenous structures and processes, the study also concluded that the relationship between hydrology, topography and geology in its original state can point the way to a logical and site-specific distribution of green and blue structures, and how a smaller scale network, dispersed throughout the urban matrix, can benefit the function of the larger-scale hydrological system.

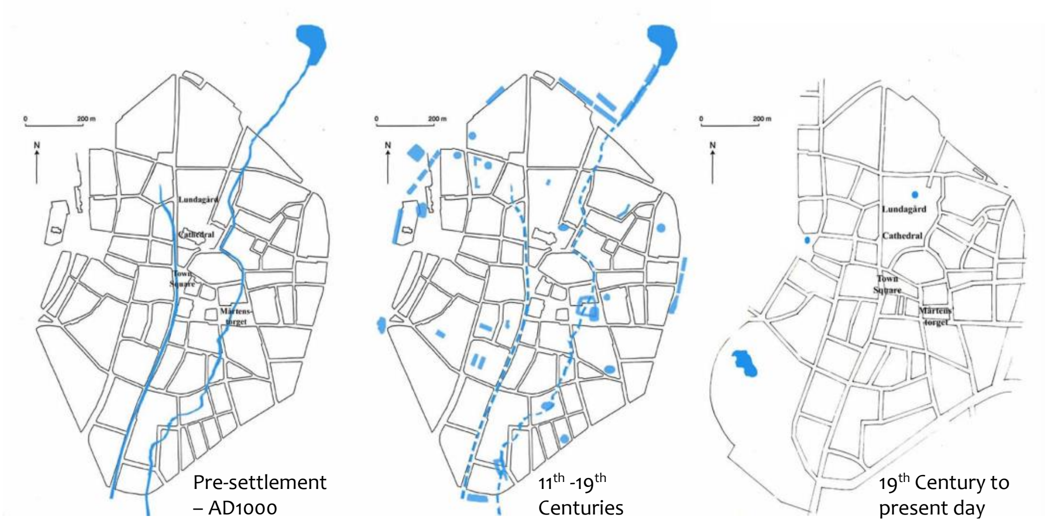


Figure 13. Maps of visible water bodies in the urban core of Lund from pre-settlement to present day. Additional mapping of green structures would give a more comprehensive picture of how disperse green structure has embedded central Lund throughout the centuries and contributed to e.g. runoff mitigation.

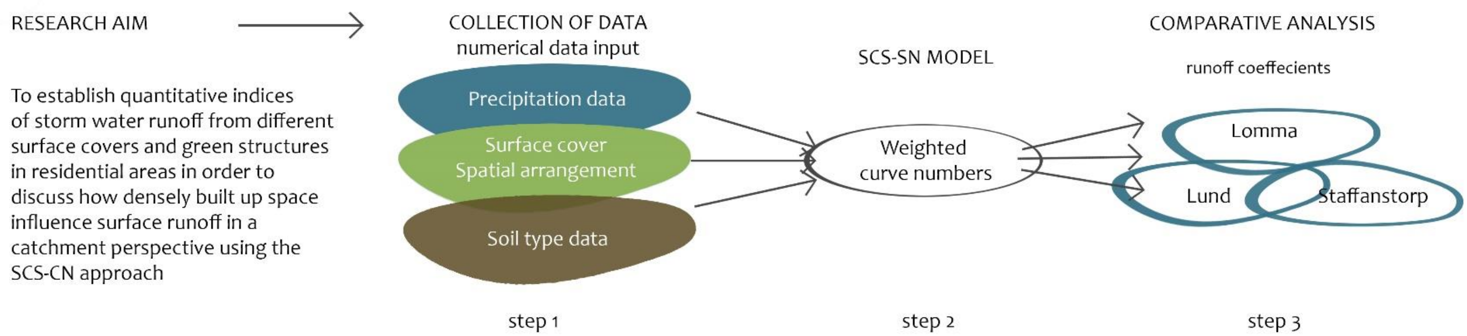
6.2 Paper II

6.2.1 Collection of input data

The methodological approach applied in Paper II involved a threefold procedure (Figure 14). The initial aim was to establish tangible and quantitative indices of storm water runoff from different surface covers and green structures in residential areas in the Höjeå river catchment. This was instigated partly by the current trend of increasing impermeable paving materials in gardens and residential courtyards and a desire to find out how this would influence surface runoff within a catchment. The case in this case study was the residential areas of the three largest urban areas within the catchment. The first step was to derive place-specific input data with regard to: 1) mean values of average precipitation events in winter and summer for the Höjeå river catchment; 2) mean values of built-up density and surface cover in residential areas in Lund, Staffanstorp and Lomma; and 3) soil type data for three urban areas.

All retrieved input data were compared against similar studies or place-specific datasets. With regard to the precipitation values, this meant that results from the analysis were equated to related research studies conducted in the same geographical area, *e.g*. by Bengtsson & Rana (2013). Surface covers and spatial distribution were based on the urban morphology types described by Gill (2006), where residential areas were classified into areas of low, medium and high density (*i.e*. density of building cover). Finally, soil type data were retrieved for comparison from three sources: the Geological Survey of Sweden (Gustafsson, 2012), the Department of Physical Geography and Ecosystems Science, Lund University (Åkerman, 2012) and a technical report conducted by J&W (1998) for the development of Lomma Harbour.

Figure 14 (next page). Conceptual diagram of the arrangement and methodological process of Paper II.


RESEARCH AIM
To establish quantitative indices of storm water runoff from different surface covers and green structures in residential areas in order to discuss how densely built up space influence surface runoff in a catchment perspective using the SCS-CN approach
COLLECTION OF DATA
numerical data input
Precipitation data
Surface cover
Spatial arrangement
Soil type data
step 1
SCS-SN MODEL
Weighted
curve numbers
step 2
COMPARATIVE ANALYSIS
runoff coeffecients
Lomma
Lund
Staffanstorp
step 3

6.2.2 The SCS-CN approach

All input data were subsequently incorporated into the surface runoff model built upon the SCS-CN (Soil Conservation Service curve number) method (now the USDA Natural Resources Conservation Service (USDA NRCS) (NRCS, 1986). This was so that numerical values (runoff coefficients) could illustrate how different residential areas within the catchment would contribute to surface runoff depending on surface cover and how surface runoff correlated to built-up density. Several international studies using the SCS-CN method have been conducted since its origin in the 1950s, in order to assess and find agreement between observed and estimated overland runoff to define appropriate curve numbers (Boughton, 1989). The SCS-CN method is dimensionless in that it does not consider time and runoff flow velocity. Furthermore, the model is not built to calculate non-point source water quality or erosion control, and is best suited to simulate the amount of overland/surface runoff produced by infiltration excess caused by shorter and very intense rainfall events, *i.e.* when the duration of rainfall is greater than the infiltration rate of the soil, especially if the studied watershed area lies within flat terrain with little topographical variation (Garen & Moore, 2005). This corresponds to some extent to the conditions set for the test areas simulated in this study, although the aspect of topographical variance with runoff induced by gradient flows would have had applicability to some extent. However, the study of Lund, Staffanstorp and Lomma was not intended to clarify the impact of runoff on water quality or erosion, but to give an indication of the scope of excess surface runoff generated within the residential realm during short rainfall events.

The SCS-CN approach does not consider surface runoff occurring from high watertables, but rather when precipitation exceeds the infiltration capacity of the soil (NRCS, 1986; Mansell, 2003). The SCS-CN model thus uses the assumption that the depth of runoff (*Pe*) is always less than or equal to precipitation depth (*P*). During a rainfall event some of the rainwater will be subject to interception, infiltration and surface storage (*Ia*), *i.e.* initial abstraction for which no runoff occurs. When runoff does begin, the additional depth of water retained in the catchment (F_a) is less than or equal to the potential maximum retention (S), as described in Gill (2006). Thus the potential runoff equals *P-Ia* and can be calculated according to the principle:

$$P = P_e + I_a + F_a$$

The SCS-CN method adopted in this study was based on a spreadsheet model and broadly followed the refinements made by Pandit and Gopalakrishnan

(1996) and described in Whitford *et al*. (2001) and Gill (2006). In the SCS-CN model, runoff coefficients are established from rainfall abstraction, which takes into account: (1) the amount of total rainfall, (2) initial abstraction (*i.e.* infiltration, surface storage and interception) and (3) maximum potential retention of the catchment (Whitford *et al*., 2001). The maximum potential retention is converted to a dimensionless curve number which ranges from 0 (no runoff) to 100 (total runoff) (NRCS, 1986)(Figure 15).

	A	B	C	D	E	F
1			Curve Number (CN) by hydrologic soil group AMCII (normal antecedent moisture conditions)			
2	surface cover type I used	US Soil Conservation Service land use classification equivalent	A (sandier soil)	B	C	D (more clayey soil)
3	Building	paved parking lots, roofs, driveways, etc	98	98	98	98
4	Other impervious	paved parking lots, roofs, driveways, etc	98	98	98	98
5	Tree	wood or forest: good cover	25	55	70	77
6	Tree	wintertime	27	56	71	77,5
7	Mown grass	pasture or range land: good condition	39	61	74	80
8	Green roof	sedum on 7 percent slope	87	87	87	87
9	Structural soil por paving	permeable paving subsoil constructions	74	76	80	83
10	Water	-	0	0	0	0
11	Bare soil/gravel	av of streets and roads:dirt and gravel	74	83,5	88	90

Figure 15. Example of curve numbers for different surface covers as calculated for the simulations in the paper II study. Curve numbers ranges from 0 (no runoff) to 100 (total runoff). Depending on the underlying soil group, surface cover types represent different curve numbers. Thus the curve number for tree cover can range from 25 on sandy soil (as in Lomma) to 77 (as in Lund and Staffanstorp).

Default curve numbers for all surface covers are present in the model, but additional curve numbers for trees with no leaf cover had to be calculated to represent wintertime conditions in southern Sweden – assuming that tree cover represented deciduous species (a further examination of the tree cover input data in the SCS-CN model is discussed in the section 7.2.2 of this thesis). Curve number for permeable paving was taken from the study by Hunt and Collins (2008) and that for green roofs from Getter *et al*. (2007). Depending on soil classification (with regard to soil type), each surface cover required a specific curve number. A final weighted curve number for each residential group (low, medium and high density) in Lund, Staffanstorp and Lomma was established. Different scenarios of different surface cover combinations in the residential areas were run in the model, where each scenario represented different weighted curve numbers. A scenario of existing surface cover conditions was initially simulated, followed by five different scenarios where either impermeable or permeable paving was increased (by 10%), or additional tree cover (10%) or sedum roofs on garages was incorporated. A total of six simulations was carried out for each residential category (low, medium and high density areas).

6.2.3 Comprehensive results – residential form and place-specific surface cover combinations

The output data from the SCS-CN approach included numerical runoff coefficients which were analysed and compared consistently with regard to spatial density of residential areas and rainfall events. Similarly to the comparative studies of *e.g.* Pauleit and Duhme (2000), Whitford *et al.* (2001), and Gill *et al.* (2007), the results indicated greater surface runoff where built-up density was high. Surface runoff also increased with increasing rainfall.

		Low density residential group	Medium density residential group	High density residential group
4 mm	**Soil group**	AMC II	AMC II	AMC II
Lomma	A/B	0.06	0.15	0.39
Lund/Staffanstorp	D	0.39	0.48	0.65
24 mm	**Soil group**	AMC II	AMC II	AMC II
Lomma	A/B	0.60	0.70	0.84
Lund/Staffanstorp	D	0.84	0,88	0.93
40 mm (winter)	**Soil group**	AMC II	AMC II	AMC II
Lomma	A/B	0.73	0.80	0.90
Lund/Staffanstorp	D	0.90	0.92	0.95
47 mm (summer)	**Soil group**	AMC II	AMC II	AMC II
Lomma	A/B	0.76	0.83	0.91
Lund/Staffanstorp	D	0.91	0.93	0.96

Table 1. Runoff coefficients for all residential areas in Lomma, Lund and Staffanstorp during different rainfall scenarios and current surface cover. Soil A/B is a sandy loam/silt loam in Lomma and soil D is a clay loam soil. AMC II indicates normal antecedent moisture conditions in the soil, i.e. neither too dry nor too wet. The table further illustrate how residential areas of high density on sandy loam/silt loam (Lomma) will generate equal amounts of runoff to that of residential areas of low density on clay rich soil – irrespective of rainfall scenario (see encircled values).

It was evident that soil type played a decisive role in the amount of runoff generated in the residential areas. Viewed from a catchment perspective, spatial density was secondary to soil type, which meant that a low density residential area on clay-rich soils (*i.e*. Lund and Staffanstorp) and a residential area of high density on sandy loam/silt loam (Lomma) generated equal amounts of runoff – irrespective of rainfall scenario (Table 1). However, urban development and changes in surface cover on sandier soil showed a greater tendency for a relative increase in runoff compared with similar situations on clay-rich soils – thus proving more disruptive to the hydrological balance. This was most evident during the small rainfall event (4 mm) in the high density residential area. The most beneficial scenario in terms of reducing runoff was a 10% increase in tree cover on the current arrangement in residential areas in Lomma, with a decrease in runoff of between 1 and 5%. The greatest effect (5%) occurred during the smallest rainfall event of 4 mm in the high density residential group. Differences between trees in summer (full leaf cover) and winter (no leaf cover) showed a difference of only 1-2%. On the other hand, a 10% increase in permeable paving over the current arrangement in residential areas in Lund and Staffanstorp was by far the most effective means of reducing surface runoff – giving a reduction of 1-10%. Again, the highest reduction occurred during the smallest rainfall event and in the high density residential group.

The results presented in Paper II showed the context dependency of the underlying soil type when comparing surface runoff in areas of different spatial densities. Individual surface covers of hard and soft landscaping were also shown to affect place-specific preconditions. Overall, however, the relative difference in runoff between various surface covers (as isolated components) changed depending on soil type and spatial density of the built-up area in which they were incorporated.

6.3 Paper III

6.3.1 Methodological outlook

In Paper III, the microclimate modelling tool ENVI-met was used to simulate how different combinations and strategic plantings of green structure, with specific focus on solitaire trees and fine-scale patches of green space, affect wind speed in winter and mean radiant temperature (Tmrt) in summer. The case study area was Lomma Harbour. By using ENVI-met, it was possible not only to obtain tangible and numerical values of how different combinations of dispersed green structure contribute to microclimate amelioration, but also to derive clear graphical data on how strategically placed green structure performs on neighbourhood level.

The study focused on a selected area (of completed construction) within the Lomma Harbour development comprising a site of 7.5 hectares located next to the seafront. This area is subjected predominantly to strong winds from the seaside (south-west direction), with an average wind speed of 5.6 m/s (at 10 m above sea level), although winds can easily and often reach well above 8 m/s (Meteotest, 2010; LBS, 2012). In summer, the beach (which runs parallel to the site) is frequently visited, and restaurants and shops are continually being opened throughout the neighbourhood.

The microclimate conditions in Lomma Harbour play an important role for a number of the environmental goals for the development, where strong winds in winter may *e.g.* impede energy use in buildings (Bagge, 2011) and thermal comfort (Metje *et al*., 2008). In summer, high temperatures can cause thermal heat stress, with severe physical discomfort (Kovats & Shakoor, 2005). This in turn can influence the recreational values of an area and also affect both indoor and outdoor thermal qualities.

The methodological approach thus constituted different scenarios investigating the role of dispersed green structure, mainly solitaire trees, in wind speed reduction in winter and mean radiant temperature (Tmrt) mitigation in summer. Tmrt is the combined total sum of shortwave and longwave radiation fluxes to which the human body is exposed and has the strongest influence on thermal comfort. By determining Tmrt for a given site, it is possible to calculate the physiologically equivalent temperature (PET), *i.e.* a value indicating how the human body physiologically perceives heat or cold depending on surrounding radiation, wind, *etc*.

6.3.2 ENVI-met: Modelling microclimate conditions in complex urban settings

The ENVI-met model is made up of a relatively simple one-dimensional soil model, a vegetation model and a radiative transfer model (Bruse & Fleer, 1998). Jointly, these comprise a full three-dimensional model (in both input and output) of the surface-plant-air interaction. ENVI-met is a Computational Fluid Dynamics (CFD) model and thus processes and analyses numerical data to solve problems concerning fluid flows. ENVI-met therefore takes a little longer to run than other models simulating microclimates in complex urban settings, *e.g.*

RayMan and SOLWEIG (Lindberg, 2014). In order to process the simulation, the user first needs to build the study area onto a grid cell interface. Buildings, type of vegetation, surface cover and soil type are assembled as input data on the interface and are three-dimensional to begin with. The grid cells, or mesh, comprise 300x300x35 (m) cells and each cell can have a horizontal extension of 0.5-10 m and a vertical height of 1-5 m (depending on case study area and objectives) (Huttner *et al*., 2008). For this study, grid cells of 2x2x2 (m) were chosen in order to: 1) encompass the entire study area whilst 2) still providing detail on the characteristics of green structures (Figure 16).

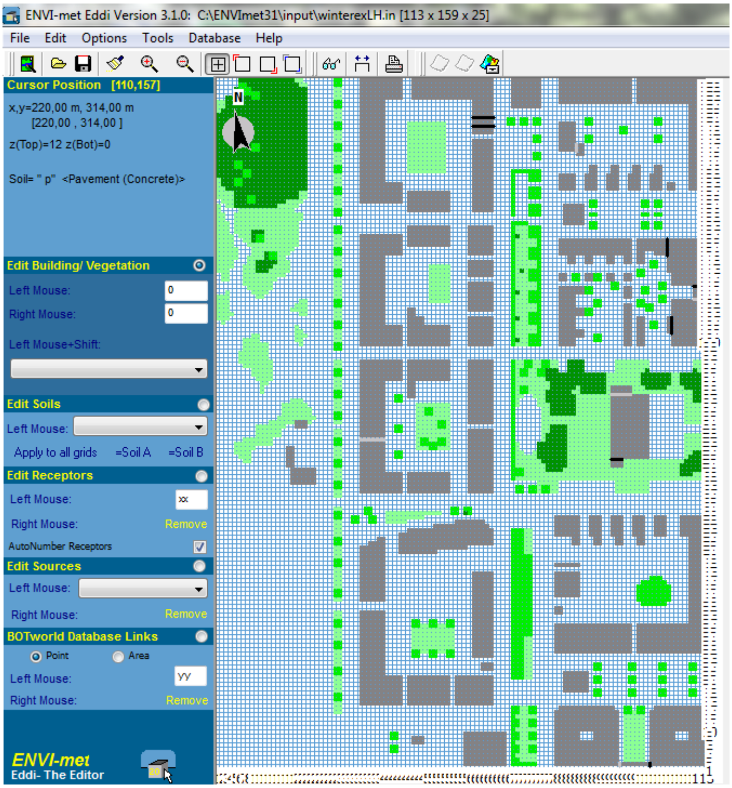


Figure 16. The ENVI-met interface for one of the simulations of the case study area in Lomma Harbour.

Additional input data consisted of numerical values, which were entered in a separate configuration file. The initial and basic input data covered geographical location (coordinates), time of year, local meteorological data on air temperature, air humidity, cloud cover, wind speed and wind direction (Huttner *et al.*, 2008). In ENVI-met, buildings are defined by their internal temperature, heat transmission by the walls and roof, and albedo values for walls and roof (Bruse, 2009). Surface covers can be defined from asphalt to concrete and brick with a range of different underlying soil types, soil temperatures and relative soil humidity values (ibid.). In the Lomma Harbour case study, surface cover was set to either asphalt and concrete paving or bare soil (underneath planting). The required input data allow calculation of Tmrt, radiation fluxes (short- and long-wave), solar direction, sunshine duration, shade, sky view factor and predicted mean vote (Huttner *et al.*, 2008). The ENVI-met model does not calculate PET, however. Therefore this was calculated using the RayMan model developed by Matzarakis *et al.* (2010) which takes into account all the meteorological parameters influencing thermal comfort (air temperature, humidity, wind speed and Tmrt).

6.3.3 Vegetation input data – leaf area index and leaf area density

Compared with many of the other microclimate models applied for simulations in complex urban settings, *e.g.* RayMan (Matzarakis *et al.*, 2010) and SOLWEIG (Lindberg, 2014), ENVI-met allows for a relatively detailed and specific make-up of vegetation. Although the default data for vegetation includes the optional input of grass and some agricultural crops, trees constitute the main category for the vegetation input.

The key input parameter in the vegetation database is leaf area density (LAD), which makes up 10 layers per plant. The LAD values help project each plant into a three-dimensional structure and each separate layer can be tailor-made to correspond to the architectural make-up of different species and/or cultivars. The sum of the 10 LAD values can in turn be converted into a leaf area index (LAI) (m^2/m^2). The LAI for *e.g.* trees represents the maximal projected leaf area per unit ground surface area and includes in this case leaves, branches and trunk (Myneni *et al.*, 1997). It is possible to calculate the LAI from the indices of LAD using the following equation:

$$\mathrm{LAI} = \sum_{i=1}^{n} \mathrm{LAD}_i \times dz$$

In order to estimate the LAD of a plant, *e.g.* a tree, the LAI of that particular species must therefore be known. This was a major concern in Paper III, since the individual architectural characteristics of the plants proposed for Lomma Harbour needed appropriate delineation and the plant database (set as default in the ENVI-met programme) did not incorporate any information on *e.g.* tree species. This is an important factor, as different trees may contribute quite differently to wind speed regulation or shade patterns. Furthermore, the subsequent LAI indices in the ENVI-met programme indicated very high values for some trees (<10.0) compared with the values reported in *e.g.* Nowak (1996), Breuer *et al*. (2003) and Nock *et al*. (2008) (range 2.0 to ∼8.8).

The default input data on vegetation in the ENVI-met programme also represented summertime conditions only, *i.e*. full leaf cover. In seasons when leaf cover for deciduous trees is absent, the LAI calculation includes branches and trunk only, and is consequently referred to as branch area index (BAI) (Kumakura *et al.*, 2011). Since the architectural make-up of deciduous trees can vary quite visibly during the winter season, with a difference in transmissivity of up to 40% (Dyer, 2013), BAI and branch area density (BAD) for the ENVI-met simulations had to be determined.

The LAD and BAD values used in the final modelling in ENVI-met were based on LAI and BAI measurements of solitaire trees in the Hørsholm Arboretum outside Copenhagen, Denmark. Using a Digital Plant Canopy Imager (CI-110) (CID, 2013), which captured wide-angle canopy images and then estimated LAI (or BAI), four digital scans of each tree species were taken on three separate field visits in summer and three separate field visits in winter (Figure 17). Each tree was scanned four times (south, west, north and east) 0.5 m away from tree trunk and 0.5 m above ground level, and a mean LAI/BAI value was then calculated from these four scans. Since the trees at Hørsholm Arboretum were planted approx. 25 years ago (with an assumed girth size of 16/18 cm when planted), all trees in the following simulations were set to a maturity of 25 years.

Additional LAI and BAI values of shrubs, grasses and perennials were determined on-site in the grounds of the Swedish University of Agricultural Sciences in Alnarp, Sweden, using the above method during summer and winter. (All tree species included in Paper III and Paper IV are listed in the Appendix).

Figure 17 (next page). Using the CI-110 Digital Plant Canopy Imager to capture images for estimations of BAI at Hørsholm Arboretum, Denmark.

6.3.4 Scenarios and simulations

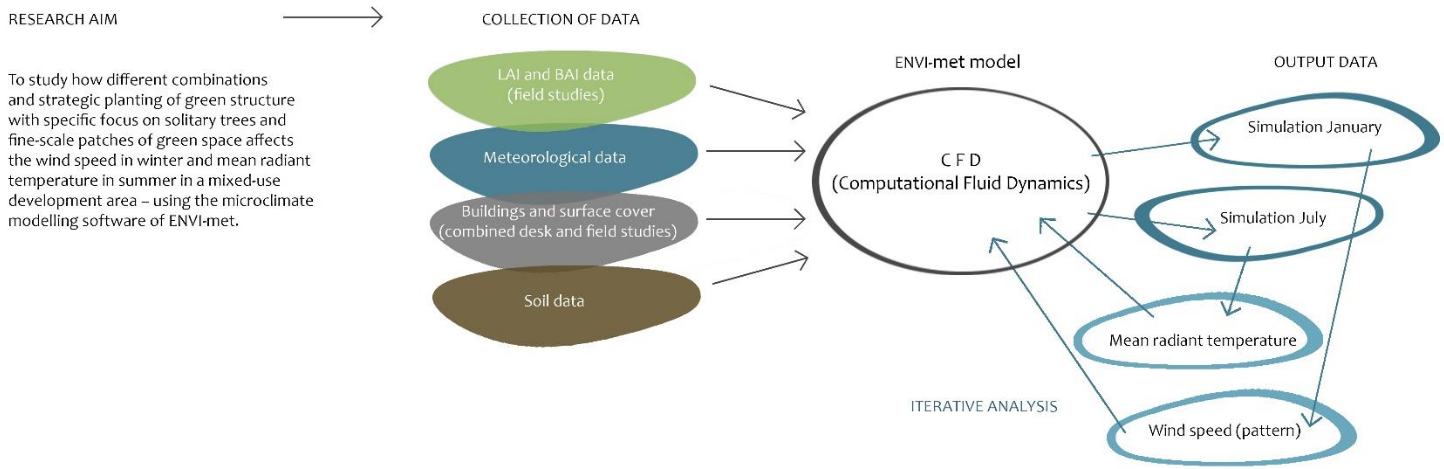
In five different scenarios, the spatial layout of roads and buildings remained the same, while the green structure arrangement was altered into different combinations except in the first scenario, where no vegetation was included. The second scenario was based on the planting plan attached to the master plan for Lomma Harbour. The remaining three scenarios comprised different alternative species and strategic placement of these in relation to the existing master plan. The method was based on iterative analyses of each simulation, in order to re-arrange the spatial layout of trees and other vegetation and examine how different combinations of green structure helped mitigate microclimate conditions. The different scenarios included summer and winter conditions and the green structure arrangement for each scenario was consistent in its spatial layout in both summer and winter simulations. In the final scenario, consideration was given to seafront views, where taller trees were planted beyond the first set of buildings (aligned to the beach area) allowing for unobstructed views.

Throughout all scenarios, attention was paid to road infrastructure and vehicular access, although in some of the scenarios vegetation was incorporated into the road infrastructure. In such cases, full possibility of vehicle flow and emergency access routes were still considered.

Each scenario was simulated for one day in January (with focus on wind speed) and one day in July (with focus on mean radiant temperature), *i.e.* two simulations for each scenario. The timeframe simulations for models in ENVI-met usually range from 24 to 48 hours, covering diurnal and nocturnal conditions. Simulations have a temporal resolution of 10 seconds during simulation, which in turn contributes to very detailed studies (Ozkeresteci *et al*., 2003). When adding a wider variety of plants to the model (as in this study), the time frame for each simulation was extended to 5-6 days, however.

Figure 18, next page, illustrates the methodological process used in Paper III.

Figure 18 (next page). Conceptual diagram of the arrangement and methodological process of Paper III.


RESEARCH AIM
To study how different combinations and strategic planting of green structure with specific focus on solitary trees and fine-scale patches of green space affects the wind speed in winter and mean radiant temperature in summer in a mixed-use development area – using the microclimate modelling software of ENVI-met.
COLLECTION OF DATA
LAI and BAI data
(field studies)
Meteorological data
Buildings and surface cover
(combined desk and field studies)
Soil data
ENVI-met model
C F D
(Computational Fluid Dynamics)
OUTPUT DATA
Simulation January
Simulation July
Mean radiant temperature
Wind speed (pattern)
ITERATIVE ANALYSIS

6.3.5 Summary of results

The comprehensive results described in Paper III show that different combinations of strategically placed green structure influenced microclimate conditions in a variety of ways, even in a complex urban configuration where space was limited (*e.g.* in a mixed-use and densely built-up area). With no vegetation at all, the case study area experienced funnelled wind patterns that could reach a wind speed in winter of >4.6 m/s in localised areas at 4 meters above ground level (scenario 1). Wind speed was reduced slightly when based on the planting scheme from the master plan (scenario 2), but this was mainly true in the centrally located park area due to the larger groups of trees planted there. Including columnar species such as *Quercus robur* 'Fastigitata Koster' near street corners close to the seafront reduced the wind speed even further, but still left localised areas of high wind velocity (scenario 3). Extending segments of woodland planting along the entire seafront, replacing all *Quercus robur* 'Fastigitata Koster' with *Pinus sylvestris* 'Fastigiata', and incorporating evergreen shrub layers of *e.g*. *Pinus mugo* underneath clear stem trees of *Sorbus intermedia* reduced wind speed throughout the area and prevented 'patches' of wind speed >4.6 m/s within the case study area (scenario 4). Keeping the sea front view clear of visual obstructions and incorporating trees taller than the buildings, *i.e*. columnar trees of *Populus nigra* 'Italica', in streets facing a west-east direction seemed to slow wind speed, only to accelerate it in localised areas further eastward within the case study area (scenario 5).

Both the winter and summer simulations were set to illustrate scenarios at 1 pm. For the simulations of Tmrt, this represented the time of day when temperatures were at their highest and also when shadows from *e.g*. trees were very short due to the solar azimuth angle (Herrman & Matzarakis, 2012). Summertime results for Tmrt showed that with no vegetation included, Tmrt increased from 43.75 °C to ~48.25 °C, except in the shade of buildings (scenario 1). The Tmrt in scenario 1 gave PET values of >34.0 °C. In scenarios 2-5 the results showed very localised effects of Tmrt mitigation, to only beneath the tree canopy. However, trees lowered Tmrt to at least 34.75 °C, and where trees were planted in larger clusters, Tmrt declined to <30.25 °C just beneath the canopy (scenarios 2-5). This is equivalent to a PET value of 22.5 °C and 20.5 °C, respectively, which indicates that the trees reduced PET by >13.5 °C compared with areas with no vegetation and areas not shaded by buildings. Although different strategic placement of different species influenced wind speed, no variation in Tmrt depending on species was observed. However, the results indicated that in tandem with reduced wind speeds, *e.g*. in scenario 4, Tmrt values increased in localised stretches (due to decreased air flow) and PET values intensified to the extreme east of dense planting structures (*e.g*. *Sorbus intermedia* with *Pinus mugo* planted underneath).

6.4 Paper IV

6.4.1 Methodological outlook

Paper IV developed as a follow-up to Paper III due to additional research questions that arose concerning how the different architectural make-up of trees influences the microclimate. Paper III aimed to illustrate how strategic planting of different green structures (predominantly trees) would influence microclimate conditions in Lomma Harbour, but the aim of Paper IV was to identify how different characteristics in architectural make-up (depending on species) might affect wind speed and Tmrt in a semi-open small public square. Thus in contrast to Paper III, it aimed for a consistent comparison approach. This meant that neither buildings nor trees changed location in the ENVI-met modelling and only the quality of the different tree species made up the variable. Moreover, while Paper III examined modification of Tmrt in summer and wind speed in winter, Paper IV focused on winter conditions only. The underlying reason and methodological approach are described in section 6.4.2 and Figure 19 illustrates the methodological process used in Paper IV.

The chosen case study area was fictional, but still representative of Lomma Harbour or any equivalent mixed-use development along the seafront of Öresund in Sweden. All meteorological and geographical data were similar to the input data used in Paper III. The reason why Paper IV did not pinpoint an area within the Lomma Harbour development was due to the spatial layout of buildings and open space required for the study. Initially, the small public square at the very south-west corner of the plan used in Paper III, *i.e*. the area of Tullhustorget, was simulated, but this area was too exposed to south-west winds, with the result that only mass planting of trees gave comparable results. Analyses of the results from these preliminary simulations indicated that the spatial arrangement of buildings and open space needed adjustment in order to: 1) reduce the number of trees used, and 2) keep a simple exposure to wind flow in the area. However, the area simulated also needed to represent a place where people would spend time (*e.g*. a small square) and where buildings would be in fairly close proximity to the trees. To satisfy such a three-dimensional scenario, the initial area of study had to be spatially modified.

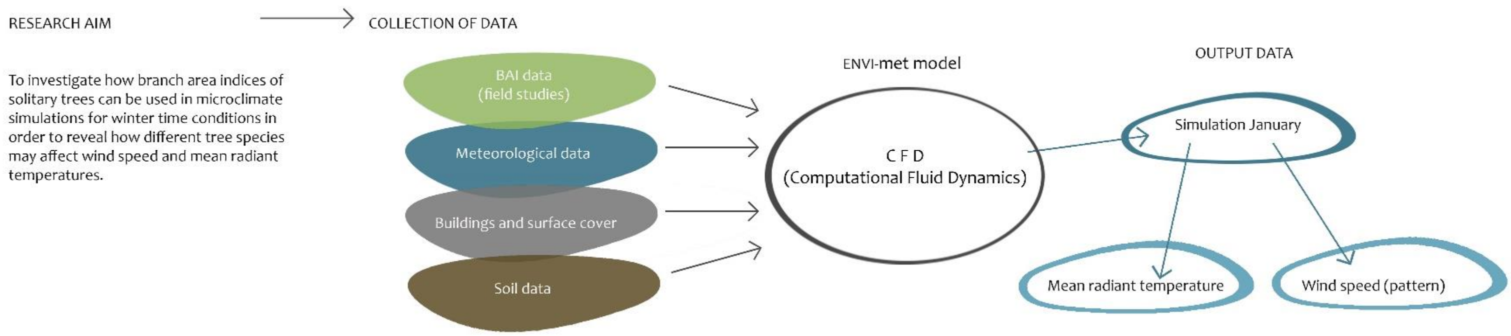

RESEARCH AIM
To investigate how branch area indices of solitary trees can be used in microclimate simulations for winter time conditions in order to reveal how different tree species may affect wind speed and mean radiant temperatures.
COLLECTION OF DATA
BAI data
(field studies)
Meteorological data
Buildings and surface cover
Soil data
ENVI-met model
C F D
(Computational Fluid Dynamics)
OUTPUT DATA
Simulation January
Mean radiant temperature
Wind speed (pattern)

Figure 19 (previous page). Conceptual diagram of the arrangement and methodological process of Paper IV.

As in Paper III, ENVI-met was used in the computational modelling approach in Paper IV. The input data on meteorological and geographical information and values of building and surface materials also followed the modelling approach in Paper III. The grid cells of the modelling interface were again set to 2x2x2 (m) and the case study area site covered ~2.5 hectares.

6.4.2 The role of branch area index and wintertime simulations

Although numerous studies exist on how urban green space and individual trees can help ameliorate different microclimate conditions in summer (*e.g.* references), limited research has been carried out on how *individual* elements of green structure, in this case solitaire trees, affect wind speed and mean radiant temperatures (Tmrt) in built-up urban areas in winter. During the initial modelling in Paper III, it was also discovered that very limited information existed on BAI for solitaire trees. While LAI constitutes an integral metric in plant data input regarding summertime simulations, BAI is central to wintertime modelling using woody plant material. The ENVI-met plant database uses a handful of default LAI values for grasses and crops, but the vast majority of the input data refer to trees.

Trees are widely regarded to help in microclimate amelioration in urban areas (Trowbridge & Bassuk, 2004; Santamouris, 2011). However, in temperate climates, where the use of broadleaved trees in the urban landscape dominates (Sjöman *et al*., 2012; Cowett & Bassuk, 2014), adequate solar transmission for *e.g*. passive heating regulation in winter is essential (Sawka *et al*., 2013). Depending on wind speed, temperatures may be physiologically experienced as several degrees lower than the measured temperature (Oke *et al*., 1989). Trees have the capacity to regulate wind speed in winter (Lindholm *et al*., 1988), thus reducing the wind chill impact. Some species have a very dense make-up of branches in winter, whereas others may present a much thinner arrangement of branch architecture. This in turn affects the magnitude of wind flow and also the extent of solar transmissivity through the canopy (Heisler, 1986; Cantón *et al.*, 1994; Konarska *et al*., 2013). As in Paper III, the aim in Paper IV was to obtain representative PET values through conversation of the Tmrt results from ENVI-met in RayMan. The wind speed was appraised at 4 m height and Tmrt at 1.20

m height. The cut at 4 m for assessing wind speed was decided because some of the trees did not provide a substantial canopy characteristic below this measurement. The height of 1.2 m above ground level was simulated for Tmrt to correspond to the average height of the centre of gravity for adults, as done by Thorsson *et al*. (2007).

As in Paper III, the BAI measurements were carried out in Hørsholm Arboretum, Denmark, using a Digital Plant Canopy Imager (CI-110) capturing wide-angle canopy images (CID, 2013). Four digital scans were taken of each tree (south, west, north and east) 0.5 m away from tree trunk and 0.5 m above ground level during three separate field visits in January. A mean BAI value was then estimated from the four scans of each tree on each measuring occasion. A total of 72 broadleaved tree species/genotypes were covered. To create an evergreen off-set, index measurements were also taken of one solitaire coniferous species (*Pinus strobus* 'Fastigiata'). A fastigiate variety was chosen to represent suitable qualities for an effective windbreak in densely built-up urban settings. All trees were of a similar age, 25 years. The following statistical analyses were performed on all BAI values obtained: 1) a box-cox transformation in order to get normal residuals, and 2) Tukey's Pairwise Comparison for descriptive statistics (Hirons, 2015).

(All tree species included in Paper III and Paper IV are listed in the Appendix).

6.4.3 Scenarios and simulations

The statistical analysis across all species indicated that the difference in BAI was highly significant ($p<0.0001$). The lowest mean BAI in the dataset was *Gingko biloba*, with a BAI of 0.27, while *Pinus strobus* 'Fastigiata' represented the largest mean BAI of 2.09. The species subsequently chosen for simulations in ENVI-met represented a selection of the intermediate and the opposite extremes from the BAI dataset. Seven simulations were run in total and included: *Ginkgo biloba*, *Acer platanoides* 'Emerald Queen', *Gleditsia triacanthos, Quercus cerris*, *Corylus colurna*, *Carpinus betulus* 'Fastigiata' and *Pinus strobus* 'Fastigiata'.

The modelling interface was created to resemble a semi-enclosed small public square (or courtyard space) of 192 m², surrounded by 12 m tall buildings to the north, east and south. No buildings or structures were placed along the west side of the square, but it was aligned with a street and a row of trees (Figure 20). Thus the trees were placed perpendicular to the wind flow and were the only obstruction to the wind flow coming from the west. For each simulation, the row of trees was altered to different species (listed above).

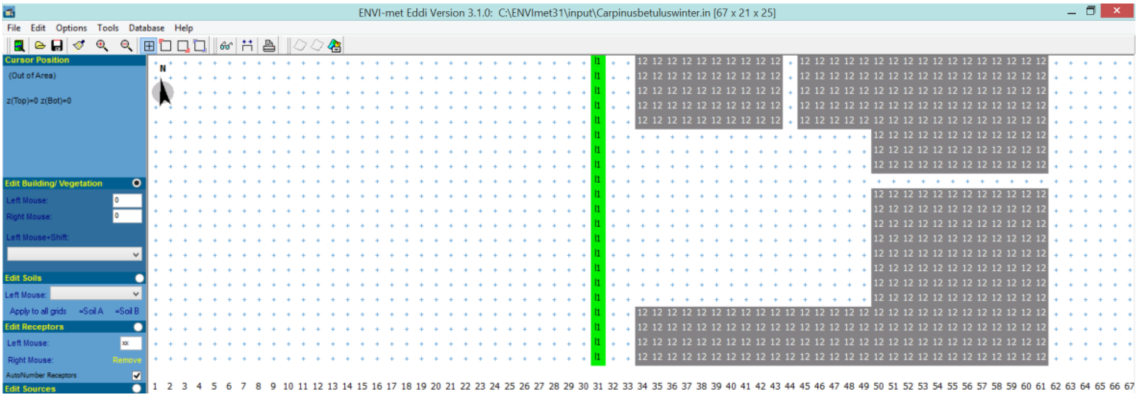


Figure 20. The ENVI-met interface of the model and the spatial layout of buildings and trees for one of the simulations for paper IV.

6.4.4 Summary of results

The results showed that wind speed on the leeward side of the trees gradually decreased with increasing BAI. The results also showed that fastigiate trees provided greater shelter from winds than clear-stemmed trees and lower BAI values. Comparing the two extremes of *Ginkgo biloga* (lowest BAI values) and *Pinus strobus* ‘Fastigiata’ (highest BAI values) showed that wind speeds above 3.60-4.10 m/s were accentuated in the public square in the scenario with *Ginkgo biloba*. The size of the area on the leeward side of the tree experiencing wind speeds above 3.60 m/s gradually decreased with increasing BAI values. In the scenario with *Pinus strobus* ‘Fastigiata’, only a limited area would experience wind speed exceeding 3.60 m/s.

In all scenarios simulating Tmrt value, Tmrt was lowest, *i.e*. between 3.15 °C and 1.25 °C in the centre of the public square. This was equivalent to PET of -6.6°C and approximately -7°C in scenarios with *Ginkgo biloba*, *Acer platanoides* ‘Emerald Queen’, *Gleditsia triacanthos*, *Quercus cerris* and *Corylus colurna* (with air temperature 0°C, relative humidity 50% and wind speed 3.60-4.10 m/s). The PET in the centre of the public square dropped to -5.9°C in scenarios with *Carpinus betulus* ‘Fastigiata’ and *Pinus strobus* ‘Fastigiata’ (with air temperature 0°C, relative humidity 50% and wind speed 3.10 m/s).

With increasing BAI, Tmrt decreased on the leeward side of the row of trees. For example, in the scenario with *Ginkgo biloba*, Tmrt values were between 5.05 and 6°C, which is equivalent to a PET of -5.4°C. In the scenario with *Pinus strobus* ‘Fastigiata’, Tmrt values were predominantly between 2.20 and 3.15°C to the leeward of the tree row, thus giving a PET of -6 to 5.9°C.

7 Discussion and conclusions

The effect of fine-scale green structure elements in modifying urban microclimate and surface runoff was scrutinised in this thesis. Modelling and analyses were used to derive quantitative and tangible values of dispersed urban green structure in line with some of the current concerns and visions of sustainable development, *e.g.* decreasing urban runoff and increasing thermal comfort in built-up urban landscapes (Wheeler & Beatley, 2014). The computational modelling served as a tool to help reveal this hidden landscape, and the studies raised questions for further discussions on how even fine-scale landscape elements can influence processes and functions beyond the site boundary. The studies also raised questions about 'quality' and 'site-specific' and about the scale of fine detail needed in order to achieve larger-scale sustainability (Capra, 1997; Levin, 1998). Such a conceptual framework, combined with the results from this thesis, could advance theories and ideas on resilience and on the role of dispersed green structure in flexibility and future vistas involving the urban landscape as a complex adaptation system (Gunderson & Holling, 2002; Berkes *et al*., 2003).

Several studies have drawn attention to the role of the urban matrix and the smaller-scale configurations and processes that occur within the built-up urban landscape (see Jacobs, 1961; Paulos & Jenkins, 2005; Burns & Kahn, 2005; Cadenasso *et al*., 2007). The way in which different arrangements of cultural and natural patterns-processes influence ordinary life and the everyday landscape (*e.g.* embedded in the urban matrix) is also integral to the European Landscape Convention (Déjeant-Pons, 2006). The studies presented in this thesis should therefore be seen as supplementary to these existing contributions. The contribution of this thesis was thus to provide additional support (using quantitative evidence) in illustrating whether, how and why small-scale green structure configurations play important roles in the complex settings of the urban landscape.

The following sections discuss each of Papers I-IV with regard to: 1) the methodological approach, 2) subsequent results and 3) further implications for green infrastructure planning and sustainable urban development. Where applicable, the SCS-CN method and ENVI-met modelling are discussed regarding their function as a green infrastructure planning tool.

7.1 Paper I

7.1.1 Methodological reflections

The rainfall events and subsequent flooding in 2007 gave a timely opportunity to study how landscape patterns in the catchment area of Höjeå river could be linked to hydrological processes (*e.g.* Bass *et al.*, 1998; Gill *et al.*, 2007). With specific focus on the spatial pattern of inner-city Lund, Paper I presents an ephemeral map of past green-blue structures and shows how the spatial arrangement and knowledge of the historical landscape may help future decision making in terms of sustainable drainage systems in a spatially compacted and densely built-up urban landscape.

As mentioned in Chapter 5, Paper I was based on a six-month research project. The terminology and use of concepts described in Paper I thus reflect my initial steps in the research discipline and show how easily misconstructions can be made. This is particularly true of how the role of *landscape process* is linked to the terms *indigenous* and *blue infrastructure*, and how these two latter concepts are used. The conceptual description in Paper I thus reflects my initial uncertainty in orientating between the traditional 'nature-culture' divide and how this resonates in the concept *indigenous,* whereas the subsequent paper concerned dispersed green structures reviewed in a historical context (and blue structures according to Swedish practice). The definitions made in Paper I suggest a normative decision about what "nature" and "natural" ought to be (as discussed in *e.g.* Spirn, 2001), whereas a thorough reflection on not maintaining the nature-culture divide so strongly might have led to other perspectives on landscape analyses. Another critical reflection on the methodology used in Paper I was how the concept 'indigenous' was mainly linked to *visible* structures of water. Within a framework of 'dispersed green (blue) structure in a historical context', additional mapping of *e.g.* ephemeral urban geology and the urban forest would have contributed additional layers of temporal structures and processes.

7.1.2 Perceiving the obscured: Structures, processes and future possibilities

During the work in Paper I, it became evident how little consideration current urban planning gives to the history of a landscape and how history and indigenous processes are not linear events in time, but an underlying guide that can also present opportunities for future sustainability (Marcucci, 2000; Spirn, 2005; Antrop, 2005). Policy documents on development strategies for Lund and discussions with representatives of Lund municipality, *i.e.* the Department of

Technical Services and Strategic Planning, revealed an absence of this knowledge. The landscape is rather addressed in its present state to fit present needs; in the case of Lund, a peripheral expansion.

Memory and recognition make up an integral part of the concept of resilience, which is described by Salat *et al*. (2014: p. 79) as "the ability of a system to evolve while keeping embedded in its structure the memory of its previous states". Knowledge of the indigenous hydrological landscape and how individual configurations of green structure (including water) were once a central part of historical Lund could thus be seen as a building block to SuDS in the town centre. While some of this information can be obtained through *e.g*. archive documents or passed down knowledge, transdisciplinary collaborations can also help reveal the hidden layers of the past, *e.g*. the archaeological heritage embedded in the landscape, and provide arguments for slow, gradual storm water infiltration throughout the town centre. Gradually increasing the area of impermeable surface cover and draining the sub-surface terrain in central Lund has dried out the soil and is disrupting the chronological layers needed for archaeological stratigraphy and interpretation of cultural sequences (Hervén, 2008).

The urban core of Lund portrays a spatially complex configuration where present preferences for SuDS seem impractical to apply (*i.e*. large-scale, visible bodies of water in this case), but Salat *et al*. (2014) describe how historical cities convey an extraordinary capacity for efficiency and resilience. The wide spectrum of fractal dimensions and spatial intricacy of small-scale configurations often creates resilient structures that have endured the destruction and reconstruction that occurs over time (Thwaites & Simkins, 2007; Salat *et al*., 2014). This argument can probably be questioned depending on the contextual nature and force of impact facing fine-scale arrangements, *e.g*. unnoticed and scattered elements of green structure may be quite vulnerable to replacement (Nowak & Greenfield, 2008). However, the concept permits spatial and structural recognition of how seemingly fine-scale and diverse configurations can make for enduring networks. Although the concept of Salat *et al*. (2014) applies predominantly to spatial planning of buildings and road infrastructure, it still indicates how disperse green structure fits into complex spatial arrangements and helps provide the urban landscape with the means to mimic natural systems, *i.e*. to infiltrate and detain rainfall on an even distribution throughout a spatially intricate and densely built-up urban landscape.

In Mossop (2006), ecological planning is described as often involving larger-scale implementations where site level and finer-scale applications are abandoned (Lunds kommun, 2010). This approach, with its decisive role, is typical of the planning and building process at present, where 'ecological' and 'sustainable' methods are addressed with a framed view and little flexibility. Incorporating SuDS in a densely built-up urban situation is predominantly viewed in terms of technical difficulties with aboveground and underground infrastructures compromising space. Associating SuDS to visibly accessible structures, or visible bodies of water, does not further aid stormwater planning and design (Miljöprogram SYD, 2009; Lunds kommun, 2010). *View* and *sight* are thus central in *seeing* the constraints or *appreciating* the large-scale solution of *e.g.* a retention pond at the urban fringe. The concepts of *view* and *sight* also show how the historical landscape and its dynamic non-linearity are hidden and obscured from tangible perception and as such, not recognised. How the patterns and processes of the past merge into palpable design for the present and the future thus coincides with a much called for discussion – a critical and constructive debate on how and why "things look the way they do" Moore (2010, p. 6) and how to translate concealed processes to a landscape literacy appreciated by both specialists and lay people (Nassauer, 1995a; Nassauer & Opdam, 2008).

7.1.3 Cultural influence – possible routes to further analyses

Studies of hydrological landscapes describe the natural routes and processes of water within a catchment and also of human intervention to profit and achieve beneficial solutions for *e.g.* travel, consumption and hygiene applications by either using or eradicating the water in the landscape (Hough, 2004). Thus it is not only the water structures themselves that represent a dynamic system in the urban fabric, but also the landscape and the cultural activities within (Mossop, 2006). In Paper I, it is not only the temporal perspective on hydrological, topographical and geological landscapes that can identify alternative directions for current SuDS implementation, but also the cultural landscape and the daily activities where water consumption has, and always will, play a most important role in people's everyday lives. However, Palang *et al*. (2011) raise the point that it might not always be "the case that past land uses should guide future ones; it might not even be desirable" (p. 346). This argument refers to the underlying motives of why certain land use came about, *i.e*. sanitary operations and drainage activity, and how health, safety, welfare, the economy and political incentives are important integral strands of the hydrological web (Spirn, 1984; 2005). Future extension and deepening of this work could therefore involve analyses of why certain decisions have been made, how this is inscribed in the current landscape and how involving public awareness of past landscapes may create alternative routes to present stormwater planning. Similar complexities can be linked to climate change mitigation and adaptation (Lorenzoni *et al*., 2007; O'Neill & Nicholson-Cole, 2009), and how this is reflected in the hydrological landscape.

7.2 Paper II

7.2.1 Modelling as method

The aim in Paper II was to derive tangible and perceptible indices showing how surface covers and green structures on a finer-scale affect surface runoff in the urban landscape, based on a similar approach as used in *e.g*. Whitford *et al*. (2001) and Gill *et al.* (2007). However, using a computer-based numerical model, such as the SCS-CN runoff model (NRCS, 1986), only provides a simulated exemplification of a hypothetically real landscape (Huggett, 1993). Working with computer-based models also imposes a certain distance between the researcher and that part of the process contained within the model itself; it requires "trust" in the simulation process (Shackley, 1997). One of the key philosophical standpoints of Hacking (1983) is the recognition of instruments and models (equipment) as constituting an integral and essential component in research. Hacking sees research as a process of reciprocal adaptation of the ingredients comprising research, whereby the various components in the research project are tweaked until a "state of stability" occurs and it is possible to delineate a result (Hacking, 1992). These ideas resonate not only with the procedural steps in Paper II (and Papers III and IV), but also with my own reflections of being in control of the model vs. working *with* the model. Regarding the extent to which models represent conditions and possible outcomes of "reality", Giere (2004: p. 747) concludes that "it is not the model that is doing the representing; it is the scientist using the model who is doing the representing". Still, data models in themselves are simplistic delineations of the real world and cause inaccuracies (Harris, 2003). The greater the apparatus (*i.e*. the more typological ingredients in interplay), the greater the likelihood of instability (Hacking, 1992). Simplifications are made with regard to *e.g.* the theoretical basis used in conceptual development of the model, the subdivision of spatial domains and the choice of mathematical methods for solving system equations (Huggett, 1993). Whilst the SCS-CN approach does not consider topographical variances or lateral base flow, it still allows comparative analysis of surface runoff from *e.g*. changes in different surface covers (Mansell, 2003).

The results from the SCS-CN modelling thus indicate the consequences for runoff volume of a specific representative scenario (due to *e.g*. change in surface cover, underlying soil group or rainfall event), but also require further discussions on how this information and actual changes in the “real world” can be interpreted (Gill, 2006).

7.2.2 Tree cover – what is it?

The results in Paper II revealed that tree cover was better at reducing surface runoff than other vegetation and permeable surface covers, irrespective of rainfall events or geographical area. However, different types of trees can play a different role in the interception and transpiration of runoff, with notable differences between coniferous and deciduous trees (Florgård & Palm, 1980; Xiao & McPherson, 2002). The needles on a pine tree make up a larger leaf area index than the leaves on *e.g*. a birch, and its contribution to rainfall interception can thus be significant during smaller rainfall events (Figure 21). This difference is particularly valuable during the winter season, when many tree species in *e.g*. the Scandinavian urban landscape shed their leaves and most precipitation events do not exceed ~4 mm (Sjöman *et al*., 2012; SMHI, 2013; Bengtsson & Rana, 2013). A study by Xiao and McPherson (2002) found that annual interception by *e.g*. *Platanus acerfolia* and *Liquidambar styraciflua* (both deciduous) differed by 3.48 m^3 when both trees had diameter at breast height (dbh) within the range 15.2-30.5 cm and the difference increased by a further 13.27 m^3 when dbh was 45.7-61.0 cm. In both cases, *Platanus acerfolia* had greater capacity for interception compared with *Liquidambar styraciflua* (Xiao & McPherson, 2002). In residential areas, where most of the mature urban canopy exists (Smith *et al*., 2005; Gill, 2006), such variance in individual species characteristics can prove quite strategic when utilising the interception of trees together with *e.g*. hard landscaping materials.

In the SCS-CN handbook (1986), curve numbers for urban vegetation cover types are based on land use, with a broad categorisation of *e.g*. lawn, parks, golf courses and cemeteries under the umbrella of ‘open space’ (NRCS, 1986). Modifications to the model have been made since then. The SCS-CN approach in Paper II was based on alterations made by Pandit and Gopalakrishnan (1996) and described in Whitford *et al*. (2001) and Gill (2006). However, the current application of *e.g*. *tree cover* provides little information on what exactly the curve number entails with regard to: 1) deciduous and evergreen leaf cover, and 2) time of year. This lack of detail on vegetation characteristics is not unique to the SCS-CN model, but also occurs in computer-based models dealing with *e.g*.

the urban climate (Matzarakis *et al.*, 2006; Lindberg & Grimmond, 2011). With an increasing number of variables with differentiating values, the complexity also increases in the computational model (Gill, 2006). Whilst interest in fine-scale detail may be merited, it may compromise the scope and scale of a possible computational simulation. This is a probable explanation why the detailed characteristics of *e.g*. vegetation are limited in computer-based models such as the SCS-CN approach, where the focus is on a large catchment scale.

Figure 21. The interception from a Pine tree illustrates how little water actually reach the ground underneath its canopy; making it impossible for the grass to grow due to lack of water (rather than lack of sunlight).

A more complex computer-based model that simulates the effects of trees on urban runoff is the Urban Forest Effects – Hydrology (UFORE-hydro) model (Wang *et al.,* 2008), and today it constitutes an integral part of the i-Tree assessment tool (USDA Forest Service, 2014). The UFORE-hydro model includes a template of 12% coniferous and 88% deciduous tree cover. The underlying tree data are taken from US Forest Service field plots, but different species characteristics are not included (Wang *et al*., 2008). Instead, the tree cover input comprise average estimates of coniferous vs. deciduous tree cover. However, consideration is given to autumn, winter and spring season, where a gradual reduction and subsequent increase in leaf cover can be simulated. By increasing tree cover from 12 to 40% throughout the study area (Dead Run catchment of Baltimore, Maryland, USA), the UFORE-hydro model concluded that runoff would decrease by 2.6% during summertime, when interception is greatest (Wang *et al.*, 2008). Similar results were found in the Adaptation Strategies for Climate Change in the Urban Environment (ASCCUE) project (2003-2006), where the Greater Manchester area in the UK was investigated in terms of urban land cover and its role in climate change adaptation and mitigation (McEvoy *et al.*, 2006). With a 10% increase in tree cover, surface runoff was found to decrease by 1.9% during a rainfall event of 28 mm (Gill *et al.*, 2007).

In Paper II, the results for winter and summer interception only differed by 1-3%. Thus although different species contribute to quite significant variations in interception at the site level (in winter and summer), the overall effect of tree interception on a larger scale (*e.g.* the city as a whole) may not be great. One conclusion could therefore be that additional variables, such as structural soil, could increase the potential of trees to mitigate surface runoff in hard-paved environments and thus increase the overall capacity throughout the urban forest. Similar assumptions have been made as regards the role of roots and their subsequent effect on increased infiltration (Bartens *et al.*, 2009; Armson *et al.*, 2013a).

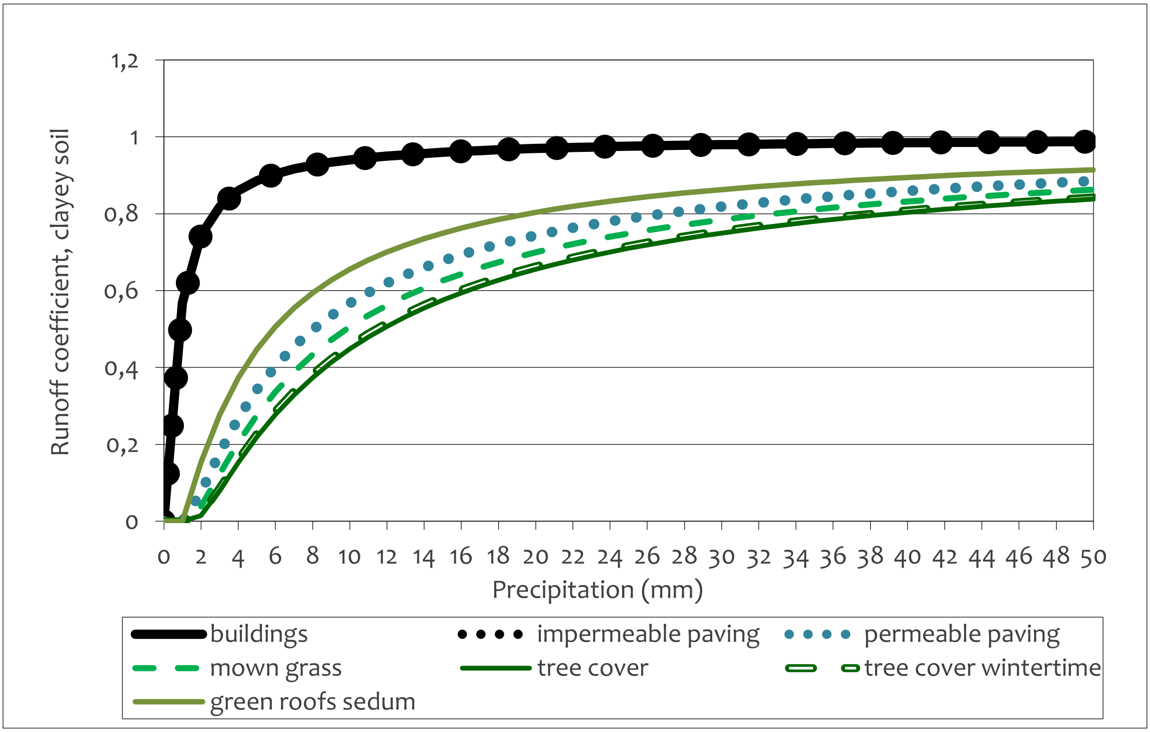
However, the results from the UFORE-hydro model and the ASCCUE project are supported by the findings in Paper II, where a 10% increase in tree cover resulted in a runoff reduction of 1-3%. The only exception was when tree cover was increased in the high density area in Lomma (sandy soil), which reduced surface runoff by 5% (in a 4 mm rain storm). However, since no explicit distinction was made as regards species or *e.g.* differences between species in structural soil, this potential would be interesting to explore further, particularly how different strategic combinations of tree species and sub-layer constructions could make up a comparative database for sustainable drainage design and runoff reduction.

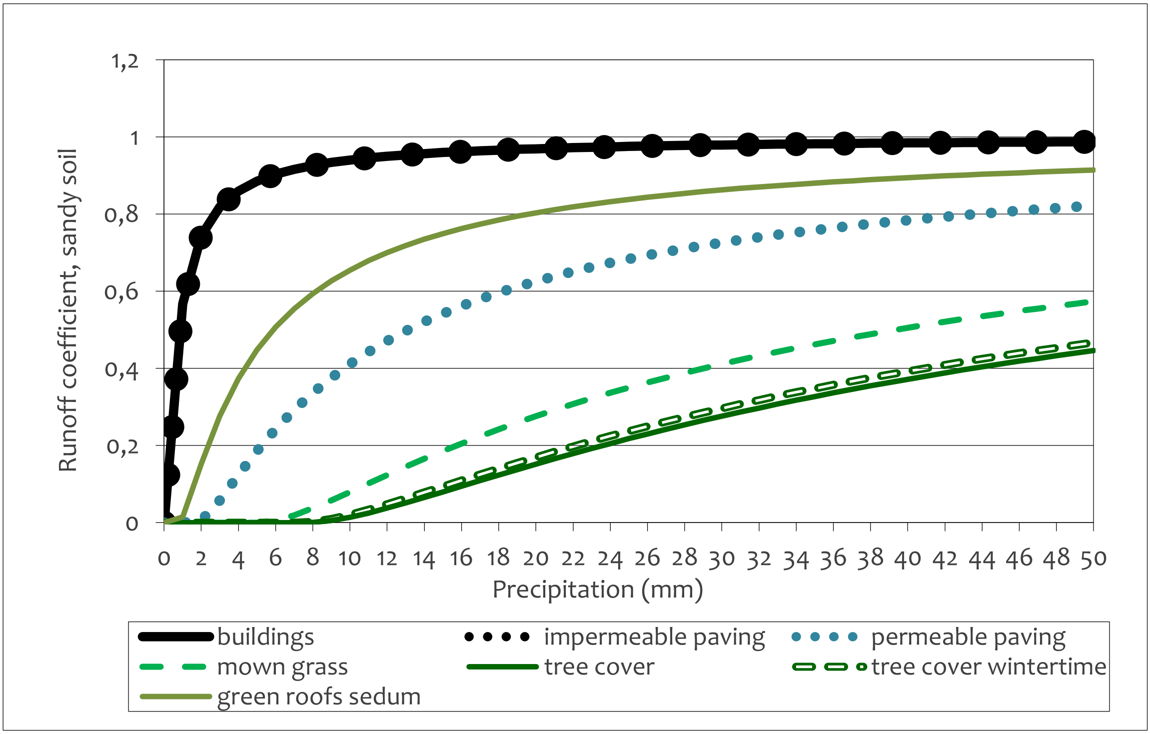
7.2.3 The role of soil and surface in storm water planning

Paper II showed how sub-surface characteristics, in terms of soil type or *e.g.* permeable sub-layer construction, are decisive for SuDS implementation in urban landscapes. Although most urban soils are no longer compatible with their natural origins, but rather modified with *e.g.* building rubble and artificial compounds (Craul, 1986; Gill, 2006), the results for the Höjeå river catchment area helped identify areas of the catchment in which different types of residential development already (or due to planned development will) affect runoff volume. No other surface cover change causes such major alteration to the hydrological balance as impermeable surface covers (*e.g.* tile and tin building roofs, asphalt and concrete paving *etc*.). Therefore a 10% increase in *e.g.* tree cover will not mitigate the runoff generated from an equal increase in impermeable surface cover (*e.g.* Gill *et al*., 2007; Paper II). However, vegetative structures and surface covers are dynamic and need to be reviewed *e.g.* 1) in their spatial context, and 2) in view of underlying soil conditions. For example, sedum cover added to garages generated a greater amount of runoff than tree cover when these were simulated as isolated and individual components (Figure 22). On the other hand, when sedum roofs were added to garages in areas with clay-rich soil, the actual runoff is either less or proportionate to the runoff compared with tree cover. The runoff from a given surface or vegetative structure should thus be assessed in relation to its actual distribution within a given spatial context – *i.e.* spatial density and underlying soil (Table 2).

Nevertheless, the role of surface area has gained paramount influence in stormwater planning in Sweden and is exemplified in a number of programmes and assessment tools where local storm water management is linked to different kinds of residential development (*e.g.* Lomma kommun, 2002; Miljöprogram SYD, 2009; Stockholms stad, 2011; Trollhättan, 2013). By applying a Green Development Index (‘*grönytefaktor*’ in Swedish), which calculates the ratio of different components within a limited area, storm water techniques are accredited, with the highest credit rating for visible water bodies (*ibid*.). Further differentiating credits are given depending on surface cover and range from *e.g.* porous grass pavers to impermeable concrete pavers, with consideration of joint width. No consideration is given to underlying sub-layers or soil type, or to how the evaluated area and its components interrelate to the surrounding landscape and the catchment. The results from the SCS-CN simulation in Paper II rather indicate that the green ratio approach, as interpreted by many municipalities in Sweden, compromises an integrated and place specific implementation of sustainable storm water management, whilst generalising the contextual qualities of space and place.

Figure 22 (next page). The diagram illustrate the runoff coefficients for different surface covers when simulated individually.


1,2
1
0,8
0,6
0,4
0,2
0
Runoff coefficient, clayey soil
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
Precipitation (mm)
buildings
impermeable paving
permeable paving
mown grass
tree cover
tree cover wintertime
green roofs sedum


1,2
1
0,8
0,6
0,4
0,2
0
Runoff coefficient, sandy soil
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
Precipitation (mm)
buildings
impermeable paving
permeable paving
mown grass
tree cover
tree cover wintertime
green roofs sedum

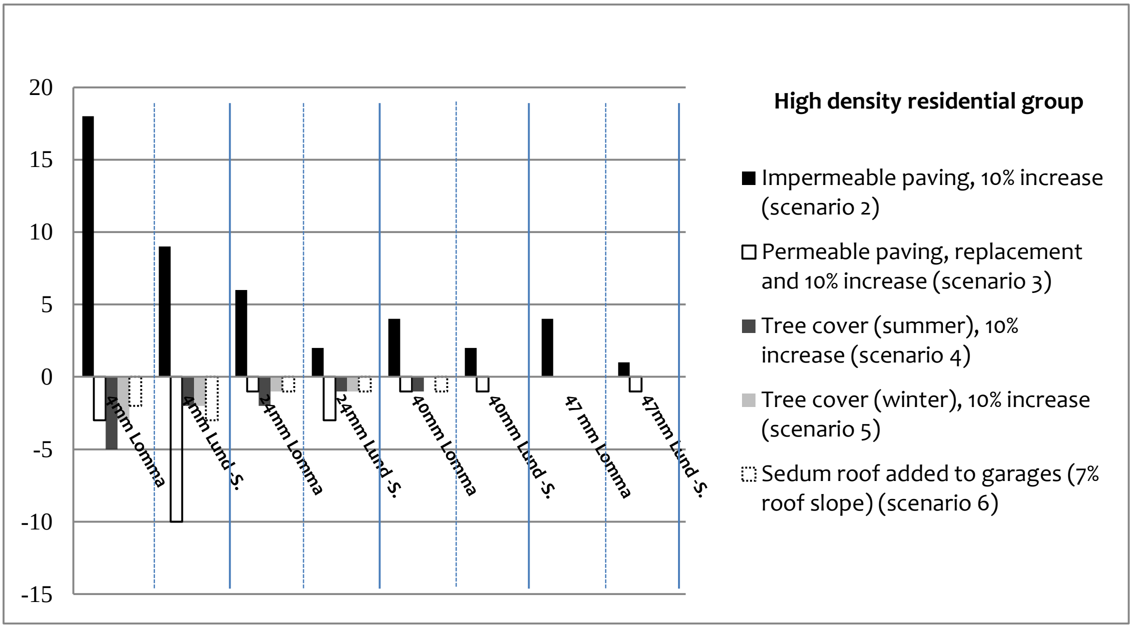


Figure 23. In areas on clay rich soil, sedum roofs and permeable paving systems can help mitigate surface runoff with a reduction of 3% and 10% compared to *e.g*. tree cover which help reduce runoff with 2% during a smaller rainfall event. Although the diagram in Figure 22 show how runoff mitigation from *e.g*. tree cover is far superior compared to *e.g*. sedum roofs or permeable paving, the above diagram illustrate how materials should always be assessed in relation to its actual distribution within a given spatial context – i.e. spatial density and underlying soil.

7.2.4 Why place-specificity matters

Site reach is a term coined by Kahn (2005: p. 291) to cover the "exchange and intersection between places, and reciprocal and nonreciprocal relations [which are] inscribed within and contributing to co-present urban spatial networks". The site (as a designer's construct) and the place (as a node of ephemeral and more enduring configurations and flows) can thus have far-reaching effects on the larger-scale cityscape (Kahn, 2005). For urban areas subjected to infill development and 'smart growth' (see Colding, 2011), or in areas where the spatial make-up already constitutes a densely woven fabric (*e.g*. medieval town centres), the purpose and function of site and place thus become pivotal. With less two-dimensional space to work with, the results presented in Paper II indicate how landscape planning in the compact city needs to embrace a four-dimensional approach where sub-surface quality and capacity become part of the design (in terms of space and time). As illustrated, two surface areas covered with permeable material and of equal proportions may not generate the same volume of surface runoff. This means that different planning considerations need to be taken with regard to underlying soil *or* sub-layer constructions, thereby creating the opportunity to elaborate with seemingly fine-scale green structure in a more diverse and place-specific context. The larger-scale hydrological catchment becomes integral to fine-scale, site-specific design and the hidden properties and potential of sub-surface configurations are shown to play a pivotal role.

While architects have struggled with the subject area of *context* over recent decades (see Isenstadt, 2005), context (in the spatial, temporal, social-ecological and political sense) has been key to the profession of landscape architecture (Swaffield, 2002). Still, it can be argued that current green space evaluation programmes as applied in *e.g*. the green ratio approach in Sweden help pull the landscape architect away from what is and should be inherent to that profession – *i.e*. context and landscape literacy (or *site* thinking and reading as referred to in Braae & Dietrich, 2012). With regard to (storm)water and the four-dimensional properties of the hydrological cycle, any fixed boundary or confinement of *place* and *site* becomes blurred. Aiming for SuDS implementations that predominantly favour visible water bodies (*e.g*. Miljöprogram Syd, 2009; Stockholm stad, 2011) rather forces an approach of "containment *within* the site" and also sets the design process of SuDS in conflict with other constellations when surface area is limited (such as recycling bins, parking lots for cycles and cars, handicap accessibility *etc*.). By focusing on available space, as seen in a blueprint for a given site, *connectivity* in its hydrological sense may well be lost. Connectivity is thus not only a concept of linear configurations visible above the surface level (Pickett *et al.*, 2004), but could just as well represent a functional network of below-surface configurations. Although seemingly small in scale, disperse green structures can be seen to function as "complementary structures" in a larger web (Colding, 2007).

7.2.5 Residential complexity – the hidden scales of residential urban landscapes

Residential areas can comprise almost 40% of surface cover in most urban landscapes, and gardens alone have been estimated to occupy 16-26% of urban land cover in Europe and up to 36% in New Zealand (Smith *et al.*, 2005; Goddard *et al.*, 2009). Although broken up by *e.g*. buildings and road infrastructure, residential suburbia can be seen as a green quilt from an aerial perspective. Even if the individual householder may not recognise how their garden area contributes to a wider provision of ecosystem services (*e.g.* runoff mitigation), the sum of all garden space contributes significantly to the green space resource in the urban landscape (Loram *et al.*, 2007).

In residential areas, the residents or the landowners are those managing and maintaining the garden or outdoor spaces and thus have a strong influence on what is planned and planted (Dunn & Heneghan, 2011). Residential areas often comprise fine-scale individual elements of green structure and, depending on their arrangement (above and below surface level), they may contribute to landscape connectivity (*e.g.* ecological linkages, extension of public space) (Mathieu *et al.*, 2007; Loram *et al.*, 2007). Changes in surface cover within a single plot (*i.e.* an increase or decrease in *e.g.* tree cover, lawn, timber decking or paved driveway) can either improve or diminish green structure connectivity (structural and functional) throughout an area and subsequently influence the hydrological balance. Changes and fluxes not only reflect spatial attributes, but also temporal phases such as the maturation of tree canopy (increasing interception) (Xiao & McPherson, 2002) and the deterioration of materials (reducing infiltration due to *e.g.* clogged pores in porous pavers) (Scholz & Grabowiecki, 2007). Flows and changes are thus strongly linked to long-term maintenance. However, the results presented in Paper II represent only one parameter (scenario) changing at a time, and therefore provide a fairly simplistic representation for ease of comparison (between different increases in surface covers and green structures). In the real world, multiple scenarios are likely to occur simultaneously, with each and every configuration possessing different qualities depending on *e.g.* age and properties.

Residential areas thus make up a large proportion of the urban landscape, whilst comprising numerous hidden processes often influenced by the caretaker of that place (Nassauer, 1995b). Hess (2005) explains how we often see and refer to *e.g.* suburbia as a “generic spatial domain”, thus missing the cultural, social and physical complexities inherent in residential suburbs. The question is to what extent individual homeowners connect their garden to the wider urban context and to the rural landscape residing beyond. Involving and informing households and homeowners to recognise their role in reducing surface runoff could be considered a decisive step in SuDS planning. Furthermore, residential areas not only act as a source and sink for runoff, but also play an active role in *e.g.* water resources. An example is the cost of water and sewer infrastructure, and how fresh water demand tends to increase with single family units compared with multifamily housing (Alberti & Marzluff, 2004). Connecting stormwater harvesting to water consumption for the purposes of *e.g.* irrigation and indoor greywater usage could therefore contribute greatly to the sustainable water management process (Pauleit & Duhme, 2000; Novotny *et al.*, 2010). However, involving private property owners in adaptive strategies to *e.g.* climate change often has financial implications and many municipalities, in Sweden and internationally, find that tax relief or economic subsidies from the government are a necessary component in the climate adaption process (Bulkeley, 2013).

7.2.6 The SCS-CN approach – concluding discussion on its applicability to planning

Several international studies on the SCS-CN method have been conducted since its creation in the 1950s to assess and compare observed and estimated overland runoff and define appropriate curve numbers (*e.g.* Boughton, 1989; Harbor, 1994; Ramakrishnan *et al.*, 2009). Garen and Moore (2005) argue that the model was never designed or intended to bring base flow, subsurface fluctuations and source location of underground lateral flows into the calculation, thus simplifying the runoff estimations. The model is suited to simulating the amount of overland/surface runoff produced by infiltration excess caused by short, very intense rainfall events, *i.e.* when the rate of rainfall is greater than the infiltration rate of the soil, especially if the watershed area under study lies within flat terrain with little topographical variation (Garen & Moore, 2005). This corresponds to some extent with the conditions set for the test areas simulated in this study, although the aspect of topographical variances would have had applicability to the urban area of Lund (a city comprising one of the largest differences in elevation within any Swedish urban area). Although the SCS-CN approach does not consider *e.g.* the contextual circumstance of sub-surface lateral flows and topographical variances within the catchment, the strength of the method lies in that it is straight-forward and user-friendly (Gill, 2006). It does not require too much hydrological/technical expertise to run the calculations and it can easily be brought into the planning process (in Paper II through an Excel spreadsheet adapted from Pandit and Gopalakrishnan (1996), by *e.g.* a landscape planner/architect. In green infrastructure planning it provides a quick estimate of the impact of different development scenarios and areas needing *e.g.* protection from surface sealing.

In the conurbations of Lomma, Lund and Staffanstorp, stormwater management constitutes an integral part of sustainable planning policies. The floods of 2007 and of later years in neighbouring catchments have helped create a recognition that previous paradigms of sewage pipe systems will not be sufficient to cope with the increasing volumes predicted in future precipitation events (Höjeå Water Council, 2013b). Planners and decision makers in Lund and Staffanstorp are also concerned with the anticipated impact any further development of new housing areas and urban infill would have on surface runoff and financial liabilities to the downstream municipality of Lomma (in the case of flood events) (*ibid*.). However, the results in Paper II illustrate that development and increased surface sealing on sandy soil (as in Lomma) would cause a greater disturbance to the hydrological balance regarding increased runoff and less percolation and infiltration than development on clay-rich soils (as in Lund and Staffanstorp). This means that political incentives and future land use planning in Lomma need to be vigilant concerning urban expansion on undeveloped land. From a purely hydrological perspective, urban development and expansion of residential areas should consider which geographical location (within the catchment basin) would cause less disturbance to the hydrological balance. In reality, other aspects and qualities need equal consideration in planning, *e.g*. potential development on fertile agricultural land, government subsidies, commerce and financial gain from urban expansion *etc.*, making a solely hydrological approach to urban development untenable.

In the substantial publication 'Water Centric – *Sustainable Communities'*, Novotny *et al.* (2010) highlight how necessary links between the macro- (watershed) scale and the micro- (individual SuDS implementations) scale need revealing in order to understand the actual impact of smaller-scale SuDS for the larger-scale sustainability of water resources and resilience to *e.g*. pluvial flooding. As previously mentioned, the SCS-CN method is at its best a good tool for providing quick and comparative indications of surface runoff at the meso-scale, *e.g*. for selected districts within a catchment area, or in macro-scale studies (*e.g.* Boughton, 1989; Gill *et al.*, 2007). The SCS-CN approach could therefore be regarded as a complementary tool to runoff assessments for urban development and green infrastructure planning (indicating areas where green structure needs protection and development). In a given planning scenario, it would thus be interesting to link the results of the SCS-CN estimation to those of other evaluation tools, *e.g*. micro-scale calculations of MIKE URBAN (MIKE, 2015) and to subsequently delineate a joint assessment through GIS (ESRI, 2015). Introducing the results from Paper II into such cross-comparisons and subsequently displaying the overall results through the dynamic interface of GIS software could provide quite an illustrative 'chain-of-events' and appraisal for strategic green infrastructure planning.

7.3 Paper III

7.3.1 The ENVI-met approach

The ENVI-met model is one of the more advanced computational modelling programmes for simulations of vegetation and surface-air interactions in complex urban settings (Lindberg, 2014). As mentioned in Chapter 5, all vegetation data in the model are based on leaf area density – an index value of the three-dimensional layering of the otherwise two-dimensional projection of LAI. The actual simulation has a temporal resolution of 10 minutes, which allows very detailed study (Ozkeresteci *et al*., 2003). Since the aim of Paper III was to incorporate different kinds of structural distributions of green structure throughout an area in Lomma Harbour, the model used quite intricate data on different characteristics of plants. This led to very long simulations and an iterative process of numerous 'trial-and-error' events before the combinations presented in the paper could be successfully simulated.

The minimum simulation time according to the ENVI-met handbook is six hours (ENVI-met, 2015), while some studies have experienced simulations stretching between 3-5 days (Bruse *et al*., 2013; Ambrosini *et al*., 2014). The initial simulations in Paper III lasted 3-7 days and the first five models stopped when the simulated time frame had reached mid-day. The immediate conclusion was that the model contained excessively detailed input data regarding the vegetation, *i.e*. too many different kinds of species in a relatively intricate distribution, and that the combined input of all data was too heavy for the software to process. In order to keep the main focus on green structure while not compromising the quality and characteristics of individual green elements, the simulated area was gradually decreased in size from initially covering the entire master plan of Lomma Harbour to a developed area covering 7.5 hectares (Paper III). A few errors and failed simulations kept occurring even when the area had been decreased in size, but eventually a balanced combination of input data and modelled interface was created. Nevertheless, each of the scenarios presented in Paper III still took an average of 6-7 days to simulate.

One of the drawbacks in using the ENVI-met software is therefore the uncertainty and time-consuming process in finding an adequate arrangement of input data for the intended scenarios. Another delay can be the default input data for vegetation in ENVI-met, which in this case were not appropriate to Lomma Harbour. When using ENVI-met, it is therefore important for the user to understand that it may be relevant to customise LAI and LAD to a more species-specific index corresponding to the situation (geographical location, time of year, growth shape of the plant). The user friendliness of the programme in *e.g.* detailed green infrastructure planning is therefore debatable, although broad estimates could be obtained fairly quickly if the input data for vegetation could be simplified (*e.g.* keeping to one species only), the geographical scope minimised, or if ENVI-met is applied in *e.g.* the planting design process, where the number of plants and size of site is limited.

Figure 24. Seminar and workshop at Lomma municipality in November 2012 concerning the ongoing and future development of green space in Lomma Harbour where the results from Paper III were presented and discussed. *Photo: Christian Almström, Lomma kommun*.

A great advantage of ENVI-met lie in its graphical representation of the results when processed through the additional programme Leonardo (part of the ENVI-met software package). The various options for graphically depicting how green structure influences the microclimate provide an illustrative and tangible representation that can be used *e.g.* to link the overarching goals of green infrastructure planning in terms of regulating ecosystem services and how these relate to site-level design and management (Dramstad & Fjellstad, 2011; Haase *et al*., 2014). For planning and political decision making, ENVI-met simulations can be beneficial in delineating the eco-technical capacity of green structure and the importance of incorporating green structure planning and design early in the planning process. This was proven in a workshop held at the local council office in Lomma and attended by city officials and representatives from the planning and building process of Lomma Harbour. The results in Paper III were presented alongside the illustrative maps from the ENVI-met simulations and it was possible to describe and further discuss how different fine-scale adjustments of disperse green structure could help modify the microclimate throughout the remaining areas of the harbour. The results could thus help encourage future decision making regarding species- and place-specific incorporation of fine-scale green structure in upcoming developments (Figure 24).

7.3.2 Tree input data

Compared with previous studies using the ENVI-met approach (*e.g*. Ali-Toudert & Mayer, 2007; Ng *et al.*, 2012; Ambrosini *et al.*, 2014), Paper III aimed to provide a detailed description of how different combinations of trees regarding architectural make-up could contribute to wind speed regulation and mitigating effects of mean radiant temperature. As mentioned in section 7.3.1, the default input data for vegetation in the ENVI-met programme did not cover appropriate indices for tree species suitable for Lomma Harbour modelling. The studies and reviews by McPherson *et al*. (1994), Nowak (1996), Peper & McPherson (2003), Breuer *et al*. (2003) and Wang *et al*. (2008) provided helpful guidance in finding credible estimates of LAI for open-grown and solitaire trees, but additional indices that would allow comparison between species were unavailable. A key reason for calculating accurate and site-related indices of leaf and branch area was to present adequate biophysical information translated into an eco-technical evaluation, comparable to the benchmarks used for building materials.

As found previously by Peper and McPherson (2003), the Digital Plant Canopy Imager (CI-110) (CID, 2013) was easy to use for estimating LAI and the process involved also some disadvantages. The batteries were quickly drained during the process of capturing and downloading the leaf area images to the computer, which caused prolonged field visits. Moreover, analysis of the images called for some subjectivity, as different threshold settings gave LAI values of great unevenness. To overcome these problems, the settings were adjusted to be consistent for each image capture and for each tree. The subsequent index was then correlated with similar indices for solitaire trees as described in Nowak (1996), Breuer *et al*. (2003) and Wang *et al*. (2008). The index values determined at the Hørsholm Arboretum, Denmark, represent a ‘snapshot’ of LAI and BAI for the given moments during the six field studies in 2013. The scenarios simulated in the Lomma Harbour study (Paper III) concerned trees aged 25 years, so further consideration needs to be taken with regard to subsequent effects on *e.g.* wind speed and Tmrt if the trees increase in height and the tree canopy matures.

As mentioned in Chapter 5, all LAI and BAI data had to be divided into 10 layers of LAD (leaf area density) and BAD (branch area density), based on an ocular estimate from observations and photographs taken at a vertical angle to each tree during the field study. It was necessary to calculate the LAD and BAD values, as they constitute the main input data for vegetation in the ENVI-met programme. They also help delineate the architectural characteristics of the tree and make it possible for the user to *e.g.* distinguish a columnar tree from a tree with a domed canopy. However, the division into LAD and BAD values could be further refined if correlated with *e.g.* a Terrestrial Laser Scanning system (TLS), which could help produce detailed data on the architectural make-up of trees (Raumonen *et al*., 2013). Further investigation is needed on how to transform the results from TLS to appropriate LAD and BAD values.

7.3.3 Comparing the results to related research

Many previous studies have examined green structure (particularly trees) and its influence on the urban climate. An extensive review by Skage *et al*. (1987) showed how the subject area had attracted scientific interest from *e.g*. the 1950s up to that time. Most of the early research mentioned in that review is based on field studies and local case studies, *e.g*. Bernatzky (1960) on comparative measurements of temperature and air humidity between vegetated and built-up areas, Herrington and Vittum (1977) on human thermal comfort in different outdoor spaces depending on vegetative cover, Murphey *et al*. (1981) on instrumentation for recording temperature differences under a tree canopy, Beckmann (1983) on windbreak affects from hedges in residential areas *etc*. The most comparable study to this thesis (Papers III and IV) mentioned in Skage *et al.* (1987) is that by Brahe (1975), which investigates how finer-scale green structures affect the microclimate in a small urban square, *e.g.* how finer-scale elements of vegetation can lower temperature, increase air humidity and increase breeze flows. The numerous research projects and scientific publications that have followed in the subject area of urban green space, individual green structure and urban microclimates in recent decades extend far beyond the scope of this discussion. The intention here is merely to give a comprehensive comparison of some these contributions to the results presented in Paper III. The primary focus is on research publications examining urban microclimate and the use of trees in urban areas within cool-temperate climate regions. The following discussion first covers the results relating to Tmrt in summer and then wind regulation in winter.

Tmrt – mean radiant temperature

Many studies examining the influence of urban green structure in cooling built-up areas have focused on the urban heat island effect and how parks can contribute to lowering diurnal and nocturnal temperatures (*e.g*. Givoni, 1991; Eliasson, 1996; Spronken-Smith & Oke, 1998; Eliasson & Upmanis, 2000; Shashua-Bar & Hoffman, 2000). A tree, for instance, will cool its surroundings actively due to evapotranspiration (converting heat into latent heat) and passively through shading (preventing the absorption of shortwave radiation of surrounding materials) (Santamouris, 2011; Dimoudi & Nikolopoulou, 2003). In complex urban settings with solitaire tree planting, these attributes are necessary to consider with regard to the orientation of nearby buildings, outdoor seating, children's play areas *etc*. (Bucht & Schlyter, 1976). Although vegetated areas are better at regulating hot temperatures, their relative effect is dependent on *e.g.* the sky view factor, surrounding building density, thermal properties and the surface albedo of materials (Santamouris, 2011; Chudnovsky *et al*., 2004). Furthermore, the cooling effect of vegetation is highly dependent on the amount of water that is available to the plant (Kleerekoper *et al*., 2012). According to Spronken-Smith and Oke (1998), the structural make-up of a park in itself also plays a decisive role for how much that park can reduce temperatures and at what point during the day. A park with continuous tree canopy coverage will achieve its peak cooling effect in the afternoon, while an open park with only a few scattered trees will exert its peak effect during the night and maintain similar temperatures to the surrounding countryside (as measured in the centre of the park) (Spronken-Smith & Oke, 1998). Different kinds of urban green space and green structure thus play different roles in how and when during the day and night they contribute to urban cooling and for this, their architectural attributes may be significant. For example, Hongbing *et al*. (2010) report that different trees (depending on *e.g*. conical, columnar and broad type) affect the daylight in buildings differently and that the architectural make-up of different trees is an important characteristic to consider in summer and in winter.

Previous studies examining the transmissivity of individual trees in solitaire plantings (*i.e*. the extent to which short-wave radiation in direct sunlight passes through the tree canopy) have included both winter and summer conditions (*i.e*. leafless and in-leaf conditions) and show how different species display different transmissivity depending on foliage and branch density (*e.g.* Gardner & Sydnor, 1984; Heisler, 1986; Canton *et al*., 1994; Brown & Gillespie, 1995; Konarska *et al*., 2013). The results in Paper III indicate that different species can affect Tmrt differently. The most pronounced difference in Tmrt between solitaire trees was found on comparing *Catalpa speciosa* (32.5-34.75 °C) and *Pinus sylvestris* 'Fastigiata' (30.25-32.50 °C), *i.e*. a Tmrt difference of 2.25 °C (at 1 pm during a day in July). In PET this would be equivalent to 22.5°C and 20.5°C, *i.e*. people would physiologically experience a 2.5 °C difference in thermal comfort. The LAI of *Catalpa speciosa* was 2.77 and of *Pinus sylvestris* 'Fastigiata' 4.80. The results also show that placing different trees and other vegetation cover in different spatial configurations influences the microclimate differently. In areas where several trees make up a coherent canopy cover, Tmrt is likely to be lower than in areas with solitaire trees – with the exception of *Quercus frainetto* in scenario 5.

However, the Tmrt values for the solitaire trees presented in Paper III are higher than those reported by Klemm *et al*. (2015), Armson *et al*. (2013b) and Konarska *et al*. (2013). In the latter study, solitaire individuals of *Tilia cordata* (in urban areas of Gothenburg, Sweden) had a Tmrt of between 24 and 30 °C. However, the trees in that study were of significant maturity (in height and volume) (Konarska *et al*., 2013) compared with the relative young specimens simulated in Paper III (25 yrs). Thus it is possible to draw the further conclusion that the influence of trees in reducing Tmrt increases with increasing tree maturity. This is also evident on reviewing the results from the scenarios presented in Paper III, where the older woodland area in the north-west corner kept a consistently low Tmrt of <30.25 °C.

Although the results in Paper III show how higher LAI may contribute to reduced Tmrt (see also Armson *et al*. (2013b) with regard to surface temperature), high LAI values do not necessarily contribute to thermal comfort in all situations. This is evident in scenario 4, where LAI was increased by planting *Pinus mugo* underneath *Sorbus intermedia*, resulting in an increase in PET to the leeward side of the planting. Vertical planting screens or columnar trees with pronounced LAI will reduce wind flow, and in summer the resulting lack of breeze may cause uncomfortable thermal stress on the human body or increase exhaust and particle concentration to the leeward side of the planting (*e.g.* Gromke *et al.*, 2008).

Wind pattern and wind speed

The effects of screens of vegetation on wind speed and wind pattern have been widely studied (*e.g.* Heisler & Dewall, 1988; Lindholm *et al.*, 1988; Rosenfeld *et al.*, 2010; Bitog *et al.*, 2012). This has traditionally been employed in *e.g.* agricultural landscapes for crop protection (Baldwin, 1988; Gustavsson & Ingelög, 1994; Brandle *et al.*, 2004) and in the urban landscape to promote thermal comfort (*e.g.* Glaumann & Westerberg, 1988), pollution dispersion (Gromke *et al.*, 2008) and energy savings in buildings (*e.g.* Simpson & McPherson, 1998). Most studies on trees and wind flow in urban situations are based on a 'single site experiment', *e.g.* wind flow assessment of one street or of one urban square, and do not take into account the spatial complexities of *e.g.* a whole neighbourhood.

Lenzhölzer (2010) tested three different scenarios for two public squares in the Netherlands using the ENVI-met model, elaborating on the basic design by placing rows of trees (for wind shelter) and solitaire trees (for shade) to obtain the most beneficial microclimate with regard to thermal comfort (from spring to late autumn). However, the results are expressed as Predicted Mean Vote (PMV) values, making it difficult to make accurate comparisons to Paper III. Moreover, the previous claim that taller trees would contribute to a reduction in wind speed compared with lower trees (*e.g.* Kjellström, 2008; Lenzhölzer, 2010) was difficult to confirm in Paper III due to the spatial complexity of surrounding buildings and orientation of road infrastructure and the subsequent wind patterns this created due to air pressure, Venturi effect and funnelled wind movement. The results thus indicate that it is difficult to generalise and create a standardised assessment of how solitaire trees could be incorporated in *e.g.* densely built-up urban areas in order to regulate wind speed. Furthermore, efforts to reduce cold wind flow into the area whilst taking into account free access to seafront views posed some complexity, as it was difficult to regulate wind speed over short distances without using the beach area for planting (scenario 5). Additional simulations based on the approach set for scenario 5 would thus be useful and interesting to explore to determine how and which green structure could be used within a dense urban fabric to reduce harsh wind in winter and still leave free access to seafront views. Avoiding wind in areas that are predominantly in the shade of buildings is one parameter that is particular important in colder climates.

Still, it is possible to argue that columnar trees with a denser architectural make-up, *i.e*. of LAI and BAI, can regulate and reduce wind speed to a greater extent than clear-stemmed trees with sparse canopies – especially when strategically positioned at street corners. This is illustrated in scenarios 3 and 4. Furthermore, the species selected for the Lomma Harbour case study were chosen for place-specific contexts. For instance, *Catalpa speciosa* is a tree that will establish and develop well in an enclosed courtyard space in the extreme south of Sweden, but will be less hardy in exposed situations and not hardy at all in northern parts of the country (Sjöman & Slagstedt, 2015). Due to the greatly varying climate zones throughout Sweden (stretching from latitude 55° in the south to 69° in the north), trees grow and develop differently depending on geographical location and climate zone. In northern Sweden, trees grow more slowly and, depending on situation, develop into much shorter individuals than in southern Sweden. The place-specific traits of different plants depending on climate zone and geographical location should thus be considered when using *e.g*. trees for climate regulation in planning and climate-responsive design.

Moreover, it is necessary to consider that the simulations presented in Paper III only represent scenarios when the wind direction is from the south-west. Although this is the prevailing wind direction, additional directions occur and on such days the effect (of the trees due to their positioning) may be very different from the results presented in Paper III. Further simulations of all scenarios applying different wind directions would also contribute to further comprehensive results.

7.3.4 Summer and winter – the need to consider both in climate-responsive planning

The results in Paper III show how both winter and summer conditions should be addressed jointly and how *e.g*. different trees contribute to microclimate amelioration differently depending on seasonal characteristics. Paper III also illustrates how it is possible to regulate and modify Tmrt and wind speed in urban areas using green structure even if space is rather limited. The results from the ENVI-met simulations of Lomma Harbour showed that even in this restricted space, the number of plants and their strategic placement and combinations affected the local climate very differently. For green infrastructure planning this indicates that it is important to question how the urban forest is being increased and where, in terms of place-specific locations, different green structures should be incorporated to fulfil multifunctional roles that are beneficial all year round.

The results presented in Paper III generally indicate that wind is an attribute to be taken into account all year round. How a species may vary in density/porosity (*i.e*. LAI and BAI) depending on summer or winter season is also necessary to consider. Although a tree may successfully ameliorate the microclimate by reducing harsh winds in the winter, the same tree can create stifling effects if air flow is prevented through its canopy in summer. Conversely, a tree that may create comfortable shade in summer may in turn impede passive solar gain in winter if planted too close to *e.g*. a south-facing building façade or overshadowing outdoor recreational areas (Bucht & Schlyter, 1976; Sawka *et al*., 2013). Still, in current urban climate research there is little recognition of how the architectural qualities of deciduous trees may differ and thus contribute to microclimate mitigation during winter. In recent studies where *e.g*. deciduous trees are studied in wintertime simulations, only a few species are investigated (Konarska *et al*., 2013) or there is a general assumption that little variation occurs between different deciduous trees during the winter season (*e.g.* Nikoofard *et al*., 2011). Throughout the initial research in Paper III, it was also evident that there has been very little research on architectural branch structure and BAI of solitaire trees and that for urban climate modelling, this creates an information gap. For green infrastructure planning in temperate urban regions, where most vegetated green structures are defoliated for 5-6 months of the year, it is therefore interesting to further explore the extent to which the disperse structure of solitaire trees may influence *e.g*. Tmrt and wind speed in winter depending on individual architectural characteristics, covering a wide array of species.

7.3.5 How the results relate to green infrastructure planning

Eliasson (2000) and Lenzhölzer (2010) describe the difficulties in applying microclimate knowledge in urban planning, claiming that the constraints are often related to excessively complicated language based on conclusions in scientific articles. Instead, straight-forward and easily depicted estimates of how *e.g*. different green structures contribute to microclimate amelioration are needed (Lenzhölzer, 2010). The ENVI-met programme is an excellent tool in this respect (as previously discussed). However, residents and homeowners also play an important role in green structure planning and design. Tree planting in a seafront development such as Lomma Harbour requires continual dialogue with residents, as trees along the beach area may generate emotional and personal conflicts by obscuring views. In Lomma Harbour these conflicts exist and in areas where different kinds of ecosystem services may collide, careful consideration of whether or not trees should be planted *or* where and which species should be of concern. Involving the community and the public in green infrastructure planning is thus an important step in creating sound governance of urban areas, promoting local stewardship in green structure management and securing long-term sustainability of the urban forest (Konijnendijk, 2003; Colding *et al*., 2006; Young & McPherson, 2013).

For many landscape professionals a viable planning approach may be when green structure, buildings and grey infrastructure are envisaged simultaneously as integrated components in order to fulfil multifunctional benefits. This is rarely the case, however, and most urban green structures are retro-fitted configurations to a fixed blueprint or to existing built-up space. If, hypothetically, the spatial grid plan of Lomma Harbour could have been re-arranged in the early planning phase to represent a spatial layout with an intricate pattern of buildings helping to break up and ease the harsh winds throughout the area, it might also have been appropriate to use a few strategically placed trees in target areas while still leaving unobstructed views of the sea.

Still, the different scenarios presented in Paper III are examples of how different green structures can affect an urban area even when the vegetation is added as a secondary layer to existing built structure. It is evident from the results that even fine-scale alterations of green structure may have large-scale implications linked to *e.g.* thermal comfort. The scenarios in Paper III represent a given situation and take into account that the plants are well established and on their way to reaching maturity. Although the plant material for the study was chosen to be exposed to salty maritime winds, appropriate staking and irrigation in the early phase of establishment are necessary for the plants to reach successful maturity and fulfil the regulating ecosystem services described. Failing to integrate this perspective will not only lead to unsuccessful ecosystem services in terms of Tmrt mitigation and wind speed regulation, but will most likely also influence how other ecosystem services are realised. The ENVI-met simulations thus present an ideal representation that in the real world depends on suitable plant selection and appropriate management (Sjöman *et al*., 2012), whilst taking into account aesthetic qualities that can help reveal the justifiable presence of incorporated green infrastructure (Nassauer, 1992; Moore, 2010).

7.4 Paper IV

7.4.1 Delineating BAI and its use for ENVI-met simulations

Paper III revealed that very limited information existed on how different tree species vary in BAI in wintertime simulations in computational modelling (Bruse, 2009). The first task of the methodological process in Paper IV was thus to analyse all the BAI values measured at the Urban Tree Arboretum at Hørsholm to determine whether any significant deviation existed between the different species (and genotypes). The data showed clear differences between species and genotypes and also between genotypes of the same species ($P<0.0001$). For a climate-responsive design, the results conclusively demonstrated the value of being selective when choosing tree species, and even genotype. The BAI data in this case helped illustrate a wider range of indices to be applied for *e.g.* climate modelling in winter and thus provided additional information on how different trees in complex urban settings contribute to microclimate amelioration, as discussed in *e.g.* Cantón *et al.* (1994), Brown and Gillespie (1995), Konarska *et al.* (2013) and Sawka *et al.* (2013).

Converting BAI to BAD followed a similar procedure as applied in Paper III, where estimates based on ocular site observations and photographs taken during the field study helped in making each BAD layer. As mentioned in the discussion in Paper III, such estimates could perhaps be further improved by applying a Terrestrial Laser Scanning approach (TLS) as described in Raumonen *et al.* (2013). Furthermore, the ENVI-met model calculates LAD values only. In all the scenarios presented in Paper IV, the BAD input data thus resembled LAD data, albeit with very low values. This gave rise to certain inaccuracies where *e.g.* the latent heat fluxes from evapotranspiration would not in effect occur during defoliated conditions. Refinement of current microclimate models (*e.g.* ENVI-met and RayMan) to consider defoliated trees for wintertime simulations may therefore be necessary in order to apply BAI data more accurately.

7.4.2 Linking the results to related research

In cold-temperate regions, protection from the wind is a primary consideration regarding thermal comfort (Brown & Gillespie, 1995). For most urban areas in *e.g.* northern Europe, cold winter winds are thus a critical parameter to take into account with regard to *e.g.* outdoor recreation and energy use in buildings (Glaumann & Westerberg, 1988; Akbari *et al.*, 2001). In winter, wind speeds reaching over 4.5 m/s are reported to create thermal distress and significant wind chill effects in cold air temperatures (Oke, 1987; Glaumann & Nord, 1993), although Lenzhölzer (2010) describes how wind speeds above 2 m/s may inhibit activities in *e.g.* public squares or other outdoor recreational areas. This in turn can influence transportation preferences in *e.g.* using motor-driven vehicles instead of walking or cycling, thus indirectly affecting a sustainable approach to travel and mobility in the urban landscape (Kronvall, 2005; Nikolopoulou & Lykoudis, 2006).

Using vegetation with moderate porosity as windbreaks is generally considered a better alternative than artificial, more solid screens (Lindholm *et al.*, 1988). Coniferous plants may create too dense screens (consequently increasing wind turbulence), but deciduous plants offer a wider range of options regarding porosity. However, the results described in Paper IV show that porosity itself varies between different tree species in winter (with one coniferous species as off-set). Compared with Paper III (where a more random and elaborate combination of different green structures was placed throughout a spatially complex residential area), Paper IV used a simpler spatial form with a consistent configuration of one species only for each simulation. It is thus easier to make comparisons to traditional estimates of windbreak effects. According to Oke (1987), a general view is that the lee cavity behind a windbreak can extend to 10 or 15 times the height of the windbreak (depending on its porosity). Although a denser windbreak of *e.g.* a leylandii hedge would reduce wind speed more immediately behind the screen, a windbreak of 40-50% permeability would affect a larger area beyond the screen (lee cavity) although with less effect on the wind velocity (Bucht & Schlyter, 1976; Brown & Gillespie, 1995). In the scenarios portrayed in Paper IV, the public square behind the windbreaks covered an area of 36 m x 24 m, *i.e.* a potential lee cavity of 3 to 4.5 times the height of the windbreak. However, the ENVI-met simulations showed only differentiating results in terms of reduced wind speed within the initial 24 m and almost no variation in either wind speed or wind pattern for the last remaining 12 m. Additional simulations would therefore be interesting to examine how different windbreaks affect the screening effect (of wind speed and pattern) when the spatial scale of surrounding built structures is varied. Nonetheless, wind speed does not tell the whole story and additional parameters such as Tmrt, air temperature, air humidity *etc.* will in effect influence how thermal comfort is actually perceived (Höppe, 2002). It could be argued that a different appraisal of windbreak character applies to urban landscapes, where the overall spatial layout can be rather complex; *e.g.* indicating densely built configurations and limited open space. For instance, PET values were lower for *Carpinus betulus* 'Fastigiata' than for *Ginkgo biloba* in the immediate leeward zone behind the tree row, even though the *Carpinus* helped reduce wind speed to a greater extent than the *Ginkgo*. In the centre of the courtyard, however, the same *Carpinus* species increased the PET by 1.1 °C compared with *Ginkgo* due to decreased wind speed and reduced wind chill effects.

Note that the results presented in Paper IV apply for wind speeds at 4 m height (above ground level). Had the level been lowered to *e.g*. 1.1 m (equivalent to the representative level of Tmrt at pedestrian height; *e.g*. Thorsson *et al*., 2007), more pronounced distinctions in wind speed regulation would arise between *e.g*. clear-stemmed and fastigiate individuals. Furthermore, the trees used in the study were fairly young specimens, and with age the branch structure and porosity will change, as will the likely results of microclimate moderation (Yates & McKennan, 1988), in this case less wind velocity on the leeward side of the trees.

While some species are undoubtedly better suited as windbreaks in winter, *e.g.* columnar species of *Carpinus betulus* ‘Fastigiata’, the same species might cause troublesome effects if planted in close proximity to south-facing facades, preventing passive solar gain to buildings (Figure 25). In the northern hemisphere, the solar azimuth projects a low angle throughout the winter and in a northerly country like Sweden the solar angle and consequent shade differ drastically between southern parts of the country (at 55° latitude) and the most northern parts (at *e.g*. 67° latitude). The solar angle and the position of objects (such as trees or neighbouring buildings) will therefore influence the length of shade areas depending on geographical location and distance to *e.g.* a given building/or outdoor recreational area (Sawka *et al*., 2013). This impact will be most emphasised in the afternoon and evening.

Figure 25 (next page). The branch architecture of trees can be very different depending on species and age. Whilst one species (*e.g*. *Carpinus betulus* ‘Fastigiata’, left) may be beneficial as wind breaks in strategic locations during winter it can also cause negative effects regarding passive solar gain if planted too close to *e.g*. a south facing buildig facade. Other species may not work as appropriate wind breaks but provide sufficient solar transmission (*e.g. Ginkgo biloba*, right).

Throughout the day, materials in the urban environment will reflect and absorb incoming solar radiation and subsequently emit longwave radiation during the night (Erell *et al*., 2011). Passive solar gain is thus seen as a contributing factor to reducing energy use in winter, and trees planted to the south-east, south, and south-west may in fact have negative consequences, increasing heating demand and causing loss of natural light (Nikoofard *et al*., 2011). The results presented in Paper IV illustrate how Tmrt declined just below or in proximity to the leeward side of the trees as BAI values increased. For example, species with a low BAI value, such as *Gleditsia triacanthos* and *Ginkgo biloba*, contributed to a 2.85 °C increase in Tmrt compared with columnar and fastigiate species, *e.g*. *Pinus strobus* 'Fastigiata' and *Carpinus betulus* 'Fastigiata'. As no equivalent comparison with regard to Tmrt was conducted by *e.g*. Konarska *et al*. (2013) or Cantón *et al*. (1994) it is difficult to reliably compare the results presented in Paper IV to those of equivalent studies. However, both Konarska *et al*. (2013)

and Cantón *et al*. (1994), who primarily investigated the transmissivity of different tree crowns, concluded in their discussions that species with low transmissivity will most likely impinge on *e.g*. passive heat gain compared with species with high transmissivity. Regarding outdoor seating and recreation space, trees with lower BAI and with late foliage would be more appropriate to incorporate, since their shading effect on Tmrt would be less and thus help dry out playground areas and allow for solar heat gain in areas for seating and rest. On the other hand, they would also allow for wind velocity to pass through the canopy, and on windy days solar access might be negligible if wind flow affected PET negatively (Lenzhölzer, 2010).

7.4.3 Linking the results to green infrastructure planning

Like Paper III, Paper IV increased understanding of how even fine-scale adjustments in green structure quality (*e.g.* in architectural make-up and BAI) can influence the overall function of green infrastructure with regard to site-related ecosystem services (in this case microclimate modification). Instead of seeing the urban forest as a dormant capital throughout the 5-6 months of the year when most trees are defoliated, the results in Paper IV reveal that fine-scale characteristics of urban green infrastructure matter in winter. This further emphasises how clearer indications of *e.g*. species quality can help guide climate-responsive planning and design to confident decision making regarding green structure selection and strategic positioning of trees in complex urban settings.

Since the major input parameter for vegetation in the ENVI-met software relies on trees and the different LAD values concern woody and herbaceous planting, it was not possible to use other fine-scale green structures such as green roofs or systems of green walls in this study. However, several previous research studies have examined climate-responsive design during winter using green structures, *e.g*. Eumorfopoulou & Kontoleon (2009) and Wong *et al*. (2010) for green wall systems, and Castleton *et al*. (2010) and Jaffal *et al*. (2012) regarding the insulating capacity of sedum roofs in winter. Adding the results of these studies to the contribution from the Paper IV provides interesting perspectives on the role of disperse green structure and its potential to regulate ecosystem services in winter.

The results in Paper IV represent young individual trees (20-25 years) and their influence on Tmrt and wind speed will alter with increasing maturity (height, width and increased BAI). Mature trees with a higher index value will, for instance, reduce Tmrt and wind speed more effectively than juvenile individuals. Variations in BAI (and LAI in summer) may also occur within the same species group (Nowak, 1996; Breuer *et al*., 2003). This is particularly true in urban environments where *e.g*. varied growing conditions and pruning may alter area index values. The results in Paper IV need to be put in this context and landscape professionals involved in tree planning and design must consider the flexibility of how even the solitaire and individual tree will influence the microclimate differently throughout its life cycle. Moreover, Paper IV was based on a relatively simple spatial layout, and in reality more complex spatial arrangements will occur. Thus it may also be necessary to consider that in *e.g*. densely built-up areas where space is restricted, it might not be economical to align the entire street with a row of trees, but to be selective in where and for what purposes certain species are planted.

Incorporating trees into green infrastructure planning and site-level design is increasingly recognised as a necessary step in successful sustainable urban development. Notable examples can be found in current environmental accreditation systems such as LEED (USGBC, 2014), the Sustainable Sites Initiative (SSI, 2009) and the BRE Environmental Assessment Method (BREEAM, 2014). The benefits of the urban forest and its contribution to a wide range of ecosystem services are recognised worldwide, and many urban reforestation programmes and cross-sector collaborations have been initiated with the support and commitment of NGOs and charitable trusts (*e.g*. 'Plant One Million', 2015; England's Community Forests, 2015; Tree Design Action Group, 2015; the Urban Reforestation, 2015). However, discussion is limited with regard to the species which should be planted in future urban forest. In urban areas subjected to infill development, it is vital that the limited space left over for green space is designed to deliver the greatest possible level of ecosystem services and multifunctional benefits. This requires an eco-technical understanding of which species are ecologically suited for the site, as well as species characteristics likely to maximise the required ecosystem services. In temperate parts of the world, this includes planning and designing with both summer and winter seasons in mind.

8 Concluding discussion and reflection

The key aim of this thesis work was to provide tangible information and quantitative indices on how fine-scale green structure in the urban landscape contributes to the regulating ecosystem services of runoff mitigation, Tmrt amelioration and wind speed regulation. Computational modelling was used in order to describe these landscape functions and how they further correspond to sustainable urban planning in the Öresund region in Sweden, particularly in the Höjeå river catchment area and the Lomma Harbour development. Throughout the course of the work, during workshops and evening seminars the results from the modelling were presented and discussed with planners and decision makers in the Höjeå area and representatives from the planning and building process of Lomma Harbour. Their response and input proved very beneficial to the overall progress of the thesis (*e.g.* keeping the aims in line with current planning incentives) and helped me maintain a level-headed position on how the methodological approach can be applied to *e.g.* green infrastructure planning, as discussed in the previous chapter. The following sections aim to give a concluding reflection on how the work of this thesis relates to current green infrastructure planning and design in Sweden, and how the results can be viewed on a more general basis.

8.1 Green infrastructure planning and design – the challenge for dispersed green structure in Sweden

In an article addressing whether green infrastructure can help promote urban sustainability, Mell (2009) describes the complex issue of quality versus quantity of space and concludes that "the quality of a green infrastructure composition may meet the need of space more appropriately than in increase in its actual size". According to Mell (2009), a proportional increase in green infrastructure does not necessarily provide a comparable or larger number of ecological, economic and social benefits. This opens the way for a sound approach for addressing green space planning in the context of urban densification and smart growth (Ståhle, 2005; Kyttä *et al.*, 2013), but also provides critical perspective on how the fine-scale quality and characteristics of *e.g.* disperse green structure fit into a larger-scale planning approach. In the context of the results presented in this thesis, the performance and capacity of a green infrastructure network thus relate to the vertical qualities of green structures and to the material and spatial patterns occurring above and below surface level. As the discussion in Chapter 7 only fleetingly touched upon, additional aspects of time and change (long-term temporal fluxes and seasonal variations) and of social networks and governance (*e.g.* public and private stewardship of urban green structure) are of equal importance. Further determining how such aspects can be incorporated into green infrastructure planning and land-use classification analyses, with an underlying focus on fine-scale green structure, would thus be an interesting area for future work. This could involve a network-based analysis such as that employed by Bodin and Zetterberg (2010) to fragmented landscapes and could comprise examination of how disperse green structure needs to be coordinated with planning goals and policies with community-based involvement to "envision creative and unique landscape designs that meet local needs" (Lovell & Taylor, 2013: p. 1453).

According to Kambites and Owen (2006), green infrastructure planning can help promote a contextualised and dynamic approach to traditional planning in the urban landscape. This is especially apparent when viewed through the lens of urban ecology and resilience thinking (Cadenasso *et al.*, 2007; Pickett & Cadenasso, 2008; Colding, 2011). In Sweden, green infrastructure is a relatively new concept within statutory planning (Swedish Environmental Agency, 2012), although *green structure* as a planning concept for increased landscape function and numerous ecosystem services has been acknowledged much earlier (*e.g.* Bucht & Persson, 1995; Lindholm *et al.*, 2003). Still, there are a number of complications in current green infrastructure planning in Sweden, particularly regarding how hydrology and SuDS are addressed, as official measures do not include *e.g.* agricultural land or vacant land with permeable soil conditions (Swedish Environmental Agency, 2012). In development projects, this position is further accentuated by the Swedish green space ratio, which reflects an insensitive approach to stormwater planning and sustainable solutions for urban runoff, with little appreciation of the interrelationships between site-level characteristics, the catchment system and historical contexts (*e.g.* Lomma kommun, 2002; Miljöprogram SYD, 2009; Stockholms stad, 2011; Trollhättan, 2013; and as addressed in Emanuelsson & Persson, 2014). In a synthesis aiming to evaluate criteria dominating the mandatory green plans of larger cities in Sweden, Sandström (2002) showed that environmental quality and biological solutions to technical problems are the least recognised parameters to green structure planning. While green structure appreciation has progressed since that study, former attitudes may still explain why the eco-technical capacity of *e.g.* seemingly undersized space, fine-scale green structure and concealed configurations below surface level remain a hidden landscape to green infrastructure planning in Sweden. Additional case studies using similar approaches to that in this thesis might help bring about a gradual shift and increased recognition of green structure functions.

8.2 Supportive concepts for a disperse green structure approach

Appreciating how the multifaceted arrangement of fine-scale green structure can help to strengthen landscape resilience derives to some extent from how space is recognised in terms of configuration and quality and how different kinds of space are linked to urban contexts (Gunderson & Holling, 2002). Although the concepts of green infrastructure and urban ecology support the idea of a resilient arrangement of disperse green structure (as portrayed in this thesis), it is difficult to find coherent support from the field of landscape ecology. For instance, in '*Urban Regions*', Forman (2008: p. 318) states that: "A massive implementation of one of these fine-scale solutions [green roofs, porous asphalt, street trees, storm water swales], or several examples of all the types, could create a city where the packed people daily encounter and are attuned to the environment. Still, it would be an anthropocentric result. Only shreds of nature could thrive long term". This statement implies nature-culture opposition; suggesting nature to be a self-evident entity and too extensive in size and process to fit the urban landscape. In the perspective presented by Forman (2008), the long-term ecological competence of disperse green structure in the urban matrix is compromised, destined to failure and consequently separated from the social-ecological network described by *e.g.* Berkes *et al*. (2003).

There are other ways to address the role of disperse green structure while still keeping a landscape ecology line of attack. In contrast to the traditional patch-based concept, where patches and the structural connectivity of corridors help permeate a passive matrix, Manning *et al*. (2009) note that this perspective "may not be suited to understanding or managing [landscapes] for adaptation to climate change". With a focus on scattered trees and climate change adaptation in modified landscapes, Manning *et al*. (2006, 2009) demonstrate significant potential to influence "landscape fluidity" and propose that individual, isolated elements and the surrounding context (*i.e.* matrix) play a key role. This view links to the results in Papers III and IV, which help illustrate the necessity of putting the urban forest into almost micro-scale contexts.

The coarse-scale classifications of the urban landscape, which according to Cadenasso *et al*. (2007) only help separate social-ecological interconnections, thus require a reverse outlook (Manning *et al*., 2009). Additional studies need to be conducted to map out the hidden capacities of fine-scale green structure. As mentioned in the discussion in Chapter 7, the potential of disperse green structure lies in its *functional* connectivity rather than *structural* connectivity and its function as “complementary structures” in a larger web (Colding, 2007). Selman (2012: p. 48) states that although it is “assumed that a fragmented and degraded landscape will lose its resilience to future stresses, reinstating [its] functional connectivity will tend to improve its adaptive capacity”. Against a background of climate change, the local, small configurations (*e.g.* fine-scale green structure) that are often familiar to urban residents (in residential areas) and the community (in mixed-use development) permit a productive approach to navigating these transitions (Folke *et al*., 2010).

8.3 Quantifying fine-scale green structure

Calculating quantitative data regarding landscape function and the ability to demonstrate tangible, numerical values of fine-scale green structure formed a significant proportion and scope of this thesis. Thus, it is interesting to recap on why such an approach is critical. Means for quantifying and attributing numerical values to what could otherwise be perceived as seemingly elusive arrangements have their roots in traditional natural science, for the purpose of constructing repetitive and generalisable data and process (Persson & Sahlin, 2013). In ‘*Trust in Numbers*’, Porter (1996) explains why and how contemporary society has become dependent on faith in numerical values as an expression and recognition of impartiality and a reverence for science. In chemical medicine, the standardisation of methods and processes is seen as critical in eliminating natural variability and ensuring repetitive reliability (Porter, 1996). In the field of landscape planning and architecture, current accreditation systems of *e.g.* the green ratio approach bear further witness to demand for templates and numerical guidelines on designing and planning urban green space. The accreditation is often based on a two-dimensional approach where three-dimensional characteristics are converted into area values (Emanuelsson & Persson, 2014). The underlying rationale is that higher credits will increase the prospect of sustainable qualification. In Sweden, the trust and confidence placed in this system has encouraged the green ratio approach to be transferred from one development to another, with little regard to the geographical and social-ecological context (*ibid*.).

The quantitative results in this thesis and the outcomes presented in Papers II, III and IV show how even finer-scale green structure is place-specific and context-dependent. Calculating quantitative, tangible indices of green structure by using the SCN-CN and ENVI-met tools thus helps to portray the discrete quality of specific green structure, species-specificity and the role of sub-surface configurations for *e.g.* SuDS. However, the description is bound to a place-specific setting and to the four-dimensional qualities of time and space. The results rather show how using quantitative methods in order to standardise green space planning and design can be misleading and should be avoided. If any generalisation can be made from the work in this thesis, it is that the potential of fine-scale green structure should not be neglected in the larger web of green infrastructure planning. Like the often forgotten practice of 'indigenous' climate-responsive design (as discussed in Paper I and in the Introduction), green infrastructure design needs to be tailored to site-specific circumstances.

By using the methods described in Paper II-IV, it was possible to obtain a representative glimpse of some of the regulating ecosystem services that occur in the daily landscape. The SCS-CN method can easily be brought into the planning process by *e.g.* landscape planners and architects. In green infrastructure planning it provides a quick estimate of the impact of different development scenarios and areas that would need *e.g.* protection from surface sealing. The ENVI-met model reveals how even seemingly fine-scale green structure influences the microclimate and provides an illustrative representation that can be used to *e.g.* link the overarching goals of green infrastructure planning in terms of regulating ecosystem. For planning and political decision making, ENVI-met simulations can be beneficial in highlighting the eco-technical capacity of green structure and the importance of incorporating green structure planning and design early in the planning process. Both techniques (SCS-CN and ENVI-met) can therefore help planners and designers (in official offices or in smaller private schemes) deconstruct seemingly hidden processes and hopefully inspire innovative draughtsmanship and sustainable stewardship of urban green space.

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Appendix

Table I. The following table presents all tree species included in Paper III and Paper IV.

Latin Genus/species	English language common names	Swedish language common names
Acer campestre	Field Maple	Naverlönn
Acer campestre 'Elsrijk'	Field Maple (Dutch form)	Naverlönn
Acer negundo	Box Elder	Asklönn
Acer platanoides	Norway Maple	Skogslönn
Acer platanoides 'Columnare'	Norway Maple	Skogslönn
Acer platanoides 'Emerald Queen'	Norway Maple	Skogslönn
Acer platanoides 'Fassen Black'	Norway Maple	Skogslönn
Acer platanoides 'Globosum'	Norway Maple	Skogslönn
Acer pseudoplatanus	Sycamore Maple	Tysklönn
Acer pseudoplatanus 'Negenia'	Sycamore Maple	Tysklönn
Acer pseudoplatanus 'Rotterdam'	Sycamore Maple	Tysklönn
Acer rubrum	Red Maple	Rödlönn
Acer saccharinum	Silver Maple	Silverlönn
Aesculus carnea 'Briotii'	Red Horse Chestnut	Rödblommig Hästkastanj
Aesculus hippocastastanum	Horse Chestnut	Hästkastanj
Aesculus hippocastastanum 'Baumannii'	Baumann's Horse Chestnut	Dubbelblommande Hästkastanj
Ailanthus altissima	Tree of Heaven	Gudaträd
Alnus cordata	Italien Alder	Italiensk al
Alnus glutinosa	Common Alder	Klibbal
Alnus x spaethii	Spaeth Alder	Berlineral
Betula pendula	Silver Birch	Vårtbjörk
Catalpa speciosa	Indian Bean Tree	Praktkatalpa
Carpinus betulus 'Fastigiata'	Upright Hornbeam	Pelaravenbok
Carpinus betulus	Hornbeam	Avenbok
Castanea sativa	Sweet Chestnut	Äkta Kastanj
Corylus colurna	Turkish Hazel	Turkisk Trädhassel
Fagus sylvatica	Beech	Bok
Fraxinus americana 'Zundert'	White Ash	Vitask

Latin Genus/species	English language common names	Swedish language common names
Fraxinus angustifolia 'Raywood'	Narrow Leaved Ash	Smalbladig Ask
Fraxinus excelsior 'Robusta'	Ash	Ask
Fraxinus excelsior 'Westhof´s Glorie'	Ash	Ask
Fraxinus ornus	Manna Ash	Mannaask
Ginkgo biloba	Ginkgo	Ginkgo
Gleditsia triacanthos	Honey Locust	Korstörne
Liriodendron tulipifera	Tulip Tree	Tulpanträd
Metasequoia glyptostroboides	Dawn Redwood	Kinesisk Sekvoja
Pinus nigra	European Black Pine	Svarttall
Pinus strobus ’Fastigiata’	Sentinel Pine (fastigiate)	Weymouthtall
Platanus acerifolia	London Plane	Platan
Populus alba 'Nivea'	Silver Poplar	Silverpoppel
Populus canescens 'De Moffart'	Grey Poplar	Gråpoppel
Populus nigra ’Italica’	Lombardy Poplar	Pyramidpoppel
Populus trichocarpa 'OP42'	Western Balsam Poplar	Jättepoppel
Populus trichocarpa 'Poca'	Western Balsam Poplar	Jättepoppel
Prunus avium	Wild Cherry	Fågelbär
Pyrus caucasica	Caucasian Pear	Kaukasiskt Päron
Pyrus communis 'Beech Hill'	Common Pear	Päron
Quercus cerris	Turkey Oak	Turkisk Ek
Quercus frainetto	Hungarian Oak	Ungersk Ek
Quercis palustris	Pin Oak	Kärrek
Quercus rubra	Northern Red Oak	Rödek
Quercus robur	Common Oak	Skogsek
Quercus robur ’Fastigiata Koster’	Fastigiate Oak	Pelarek
Quercus petraea	Sessile Oak	Bergek
Robinia pseudoacacia	Lack Locust	Robinia
Robinia pseudoacacia 'Bessoniana'	Lack Locust	Robinia
Robinia pseudoacacia 'Nyirsegi'	Lack Locust	Robinia
Robinia pseudoacacia 'Umbraculifera'	Lack Locust	Robinia
Salix alba	White Willow	Vitpil

Latin Genus/species	English language common names	Swedish language common names
Salix alba 'Liempde'	White Willow	Vitpil
Salix alba 'Saba'	White Willow	Vitpil
Salix alba 'Sibirica'	White Willow	Vitpil
Sophora japonica 'Regent'	Japanese Pagoda Tree	Pagodträd
Sophora japonica	Japanese Pagoda Tree	Pagodträd
Sorbus intermedia	Swedish Whitebeam	Oxel
Tilia cordata	Small Leaved Lime	Skogslind
Tilia cordata 'Erecta'	Small Leaved Lime	Skogslind
Tilia cordata 'Greenspire'	Small Leaved Lime	Skogslind
Tilia cordata 'Rancho'	Small Leaved Lime	Skogslind
Tilia euchlora	Caucasion Lime	Glanslind
Tilia euchlora 'Frigg'	Caucasion Lime	Glanslind
Tilia platyphyllos	Broad Leaved Lime	Bohuslind
Tilia platyphyllos 'Rubra'	Broad Leaved Lime	Bohuslind
Tilia platyphyllos 'Örebro'	Broad Leaved Lime	Bohuslind
Tilia platyphyllos 'Fenris'	Broad Leaved Lime	Bohuslind
Tilia europaea 'Pallida'	Common Lime	Parklind
Tilia hybrid 'Odin'	Hybrid Lime	Hybridlind